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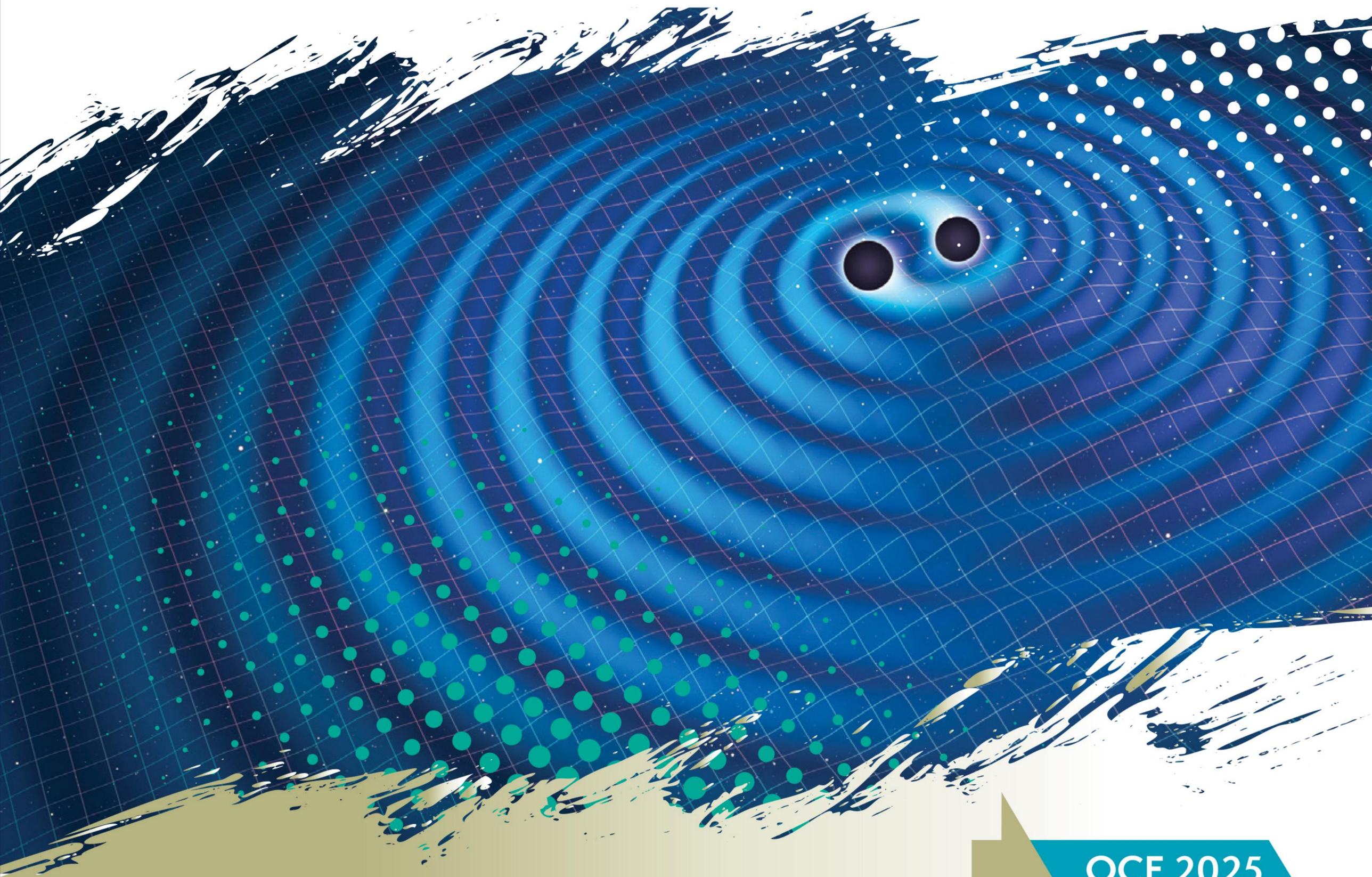
UNITS 3 & 4



Student Book

QCE 2025 Physics SYLLABUS

PEARSON

PHYSICS

QUEENSLAND

UNITS 3 & 4

STUDENT BOOK

2nd EDITION

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Syllabus
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This syllabus forms part of a new senior assessment and tertiary entrance system in Queensland. Along with other senior syllabuses, it is still being refined in preparation for implementation in schools from 2025.

For the most current syllabus versions and curriculum information please refer to the QCAA website https://www.qcaa.qld.edu.au/

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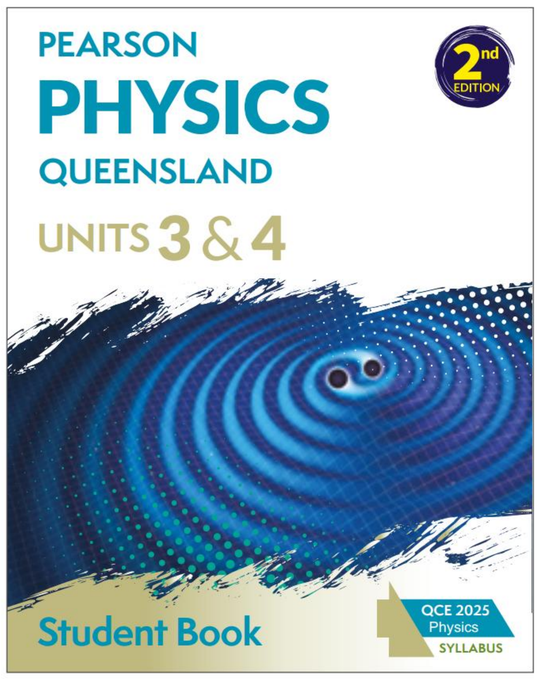

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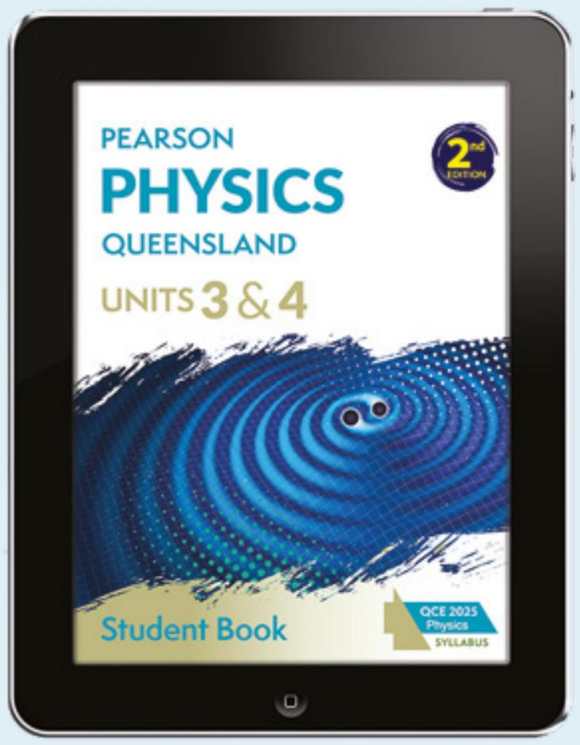

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How to use this book

PEARSON PHYSICS QUEENSLAND STUDENT BOOK UNITS 3 & 4 2ND EDITION

Pearson Physics Queensland Student Book Units 3 & 4 2nd edition has been written to the 2025 QCAA Physics Syllabus. This book includes an additional Skills and Assessment Toolkit online as well as a depth of additional resources, to support every aspect of teaching and learning. Explore how to use this book below.

Design

The best-practice literacy and instructional design supports all learners.

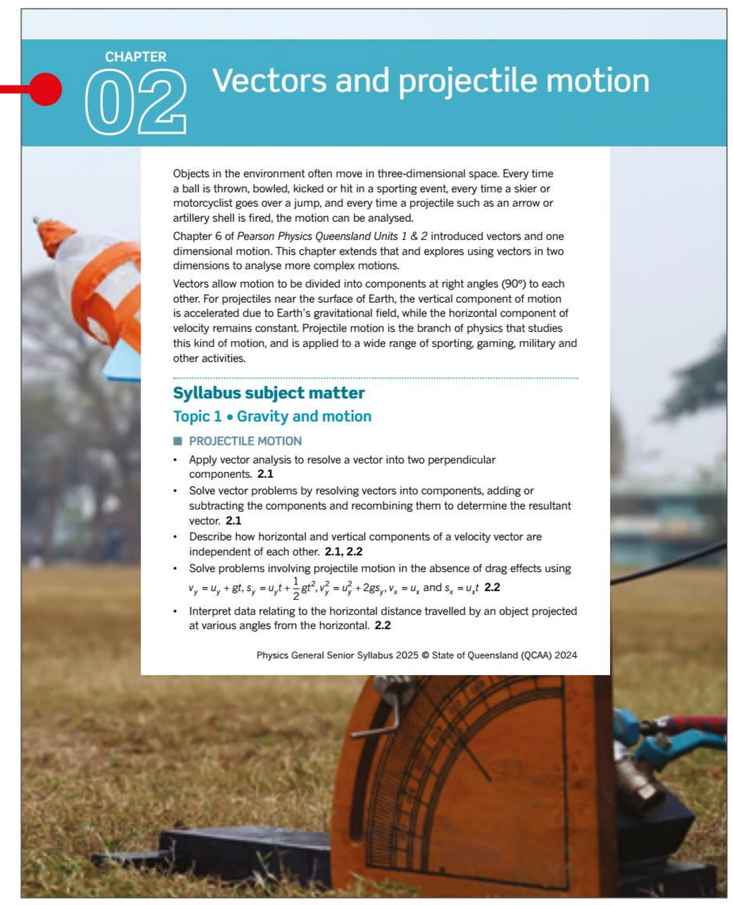
A simple-to-navigate predictable design enables ease of use. The high-quality, relevant photos and illustrations assist students' understanding of concepts.

Chapter 1

The Skills and Assessment Toolkit provides support across the Science Inquiry Skills and Assessment requirements. The material is presented as a handy reference to enable confident, complete coverage of the syllabus across the course. Reworked and fully updated to meet the evolved requirements of the revised QCE 2025 Syllabus, and to respond to the needs of teachers and students.

Chapter opener

The syllabus subject matter addressed in each chapter is clearly listed, and mapped to the modules in which the content is addressed.



CHAPTER 02 Vectors and projectile motion

Objects in the environment often move in three-dimensional space. Every time a ball is thrown, bowled, kicked or hit in a sporting event, every time a skier or motorcyclist goes over a jump, and every time a projectile such as an arrow or artillery shell is fired, the motion can be analysed.

Chapter 6 of *Pearson Physics Queensland Units 1 & 2* introduced vectors and one dimensional motion. This chapter extends that and explores using vectors in two dimensions to analyse more complex motions.

Vectors allow motion to be divided into components at right angles (90°) to each other. For projectiles near the surface of Earth, the vertical component of motion is accelerated due to Earth's gravitational field, while the horizontal component of velocity remains constant. Projectile motion is the branch of physics that studies this kind of motion, and is applied to a wide range of sporting, gaming, military and other activities.

Syllabus subject matter

Topic 1 • Gravity and motion

PROJECTILE MOTION

- Apply vector analysis to resolve a vector into two perpendicular components. **2.1**
- Solve vector problems by resolving vectors into components, adding or subtracting the components and recombining them to determine the resultant vector. **2.1**
- Describe how horizontal and vertical components of a velocity vector are independent of each other. **2.1, 2.2**
- Solve problems involving projectile motion in the absence of drag effects using $v_y = u_y + gt$, $s_y = u_y t + \frac{1}{2}gt^2$, $v_y^2 = u_y^2 + 2gs_y$, $v_x = u_x$ and $s_x = u_x t$ **2.2**
- Interpret data relating to the horizontal distance travelled by an object projected at various angles from the horizontal. **2.2**

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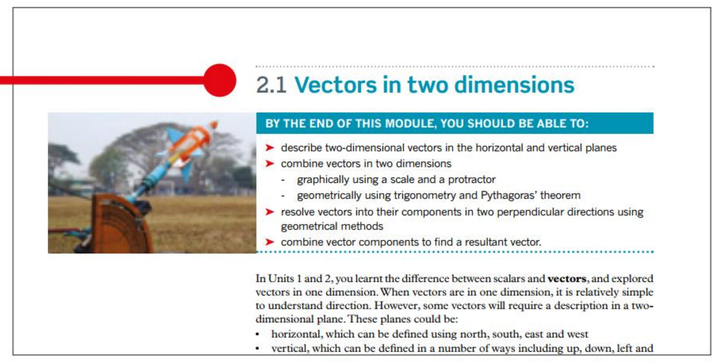
Module opener

Module openers outline the key concepts and skills to be developed and link to the syllabus subject matter listed in the Chapter opener.



2.1 Vectors in two dimensions

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- describe two-dimensional vectors in the horizontal and vertical planes
- combine vectors in two dimensions
  - graphically using a scale and a protractor
  - geometrically using trigonometry and Pythagoras' theorem
- resolve vectors into their components in two perpendicular directions using geometrical methods
- combine vector components to find a resultant vector.

In Units 1 and 2, you learnt the difference between scalars and **vectors**, and explored vectors in one dimension. When vectors are in one dimension, it is relatively simple to understand direction. However, some vectors will require a description in a two-dimensional plane. These planes could be:

- horizontal, which can be defined using north, south, east and west
- vertical, which can be defined in a number of ways including up, down, left and

Science as a human endeavour

Science as a human endeavour (SHE) features provide stimulus for the Research investigation. The SHE features are structured to develop the foundational skills relevant to supporting the relevant Science inquiry skills through the lens of Science as a human endeavour, providing a suitable foundation from which students can launch into Research investigation IA3 and draw upon building proficiency for Assessment objectives 1, 2 and 3.

SCIENCE AS A HUMAN ENDEAVOUR 4

Models of the universe

From ancient times, people have always sought ways to explain their world and their place in it. They would have looked at the sky above and decided that the heavens were under the control of various gods and spiritual identities beyond their comprehension. They observed that the Sun and Moon, together with many other bodies only visible at night, moved in predictable paths from east to west across the sky. It was this repetitive pattern which soon led to a model in which the motion of those bodies could be understood in concrete terms.

The earliest model was perhaps the most obvious one. The geocentric model (Figure 12.4.0) described the heavenly bodies as travelling around Earth in circular orbits centred on Earth (from the Greek geos for 'Earth'). Each body followed its own individual path against the backdrop of all the stars, which seemed not to move at all, but to be fixed on the celestial sphere—much like stars stuck on a bedroom ceiling. The Sun and Moon were closest to Earth, and the other members of the system—the wandering planets and comets—were at varying further distances. The immovable stars were the most distant of all.

FIGURE 12.4.1 Elaborate illustrations of the geocentric universe adorned many texts in the Middle Ages.

From years of observations, Ptolemy, a Greco-Roman philosopher in Alexandria in the 2nd century, formulated a mathematical description of the geocentric system. Ptolemy's model could be used to accurately predict the positions of the Moon and planets, as well as eclipses. As such, it can be described as an 'empirical' model: one that fits the observations and can be used to make predictions. To describe the retrograde motion of the planets, his model had to incorporate various complications such as 'epicycles'. (A planet will generally seem to move in a steady direction across the background of distant stars. However, some planets occasionally move for a short time in the opposite, or retrograde, direction). Although all orbits were perfect circles centred on Earth, the planets followed their own small orbits around centres that orbited Earth.

Ultimately, it was these complications that led to the demise of Ptolemy's geocentric model and the acceptance of the better, theoretical heliocentric or Sun-centred model. The heliocentric model had been proposed by Aristarchus (c. 310–230 BCE) but was not widely accepted because it seemed to contradict common sense.

It took some courage for Nicolaus Copernicus to publish his theory in 1543, as it contradicted the idea that Earth occupied the prime position in the universe, as implied by the Bible. While not abandoning circular orbits and epicycles altogether, Copernicus centred the planetary orbits on the Sun, and the Moon's orbit on Earth. He also:

- placed Mercury, Venus, Earth/Moon, Mars, Jupiter and Saturn in order from the Sun
- described Earth's day–night rotation, its annual solar revolution and Earth's tilted axis to explain the seasons
- showed that planetary retrograde motion was explained by Earth's motion around the Sun.

Although the Copernican model could better explain astronomical observations, it was still rather complicated and must be regarded as a stepping stone. The theories of Kepler and Newton detailed in Chapter 4, built upon these ideas as well as the modern theories which followed, such as the acceleration of the expansion of the universe evidenced by Australian Nobel prize winner, Brian Schmidt.

KEY QUESTIONS

Forming and finding

1 Contrast the key feature of heliocentric and geocentric models.
2 The article claims the expansion of the universe is accelerating. Use this claim to formulate a research question.
3 The theories detailed in the article predominantly focus on the solar system. Locate a scientifically credible source which details when humans first became aware of systems beyond Earth's, confirming the need to refine the model of the universe.

Analysing

4 What discovery lead to the eventual abandonment of the Geocentric model? With reference to the laws of motion, explain why this was necessary.
5 Explain the role of time in the collection of data required to verify a proposed model claiming to predict the motion of planets.

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Pythagoras' theorem

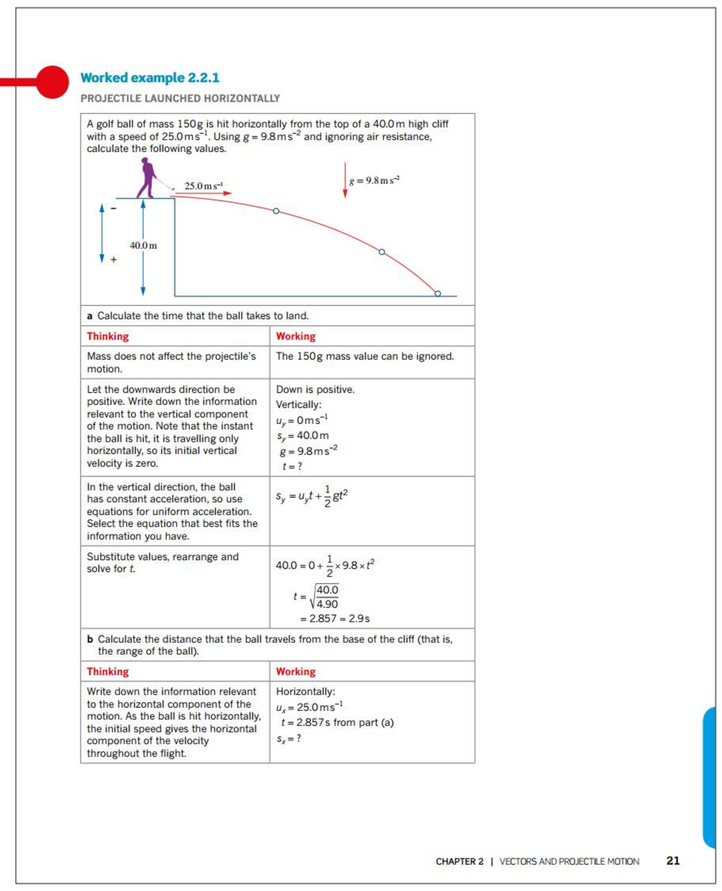
Pythagoras' theorem is $a^2 + b^2 = c^2$, where c is the hypotenuse (the longest side), and a and b are the two shorter sides of a right-angled triangle. The hypotenuse is easily recognised as it is directly across from (opposite) the right angle of the triangle.

Highlight box

Highlight boxes focus on important information such as key definitions, formulas and salient points.

Worked examples

Worked examples use sequential steps of thinking and working to model calculations and problem-solving, step-by-step. Each Worked example is followed by a Try yourself task where students apply their learning to a mirrored problem. Fully worked solutions to all Try yourself problems are available online on *Pearson Physics Queensland Units 3 & 4 2nd edition* eBook.



Worked example 2.2.1

PROJECTILE LAUNCHED HORIZONTALLY

A golf ball of mass 150 g is hit horizontally from the top of a 40.0 m high cliff with a speed of 25.0 m s^{-1}. Using $g = 9.8\,\text{m s}^{-2}$ and ignoring air resistance, calculate the following values.

a Calculate the time that the ball takes to land.

Thinking	Working
Mass does not affect the projectile's motion.	The 150 g mass value can be ignored.
Let the downwards direction be positive. Write down the information relevant to the vertical component of the motion. Note that the instant the ball is hit, it is travelling only horizontally, so its initial vertical velocity is zero.	Down is positive. Vertically: $u_y = 0\,\text{m s}^{-1}$, $s_y = 40.0\,\text{m}$, $g = 9.8\,\text{m s}^{-2}$, $t = ?$
In the vertical direction, the ball has constant acceleration, so use equations for uniform acceleration. Select the equation that best fits the information you have.	$s_y = u_y t + \frac{1}{2}gt^2$
Substitute values, rearrange and solve for t.	$40.0 = 0 + \frac{1}{2} \times 9.8 \times t^2$; $t = \sqrt{\frac{40.0}{4.90}} = 2.857 = 2.9\,\text{s}$

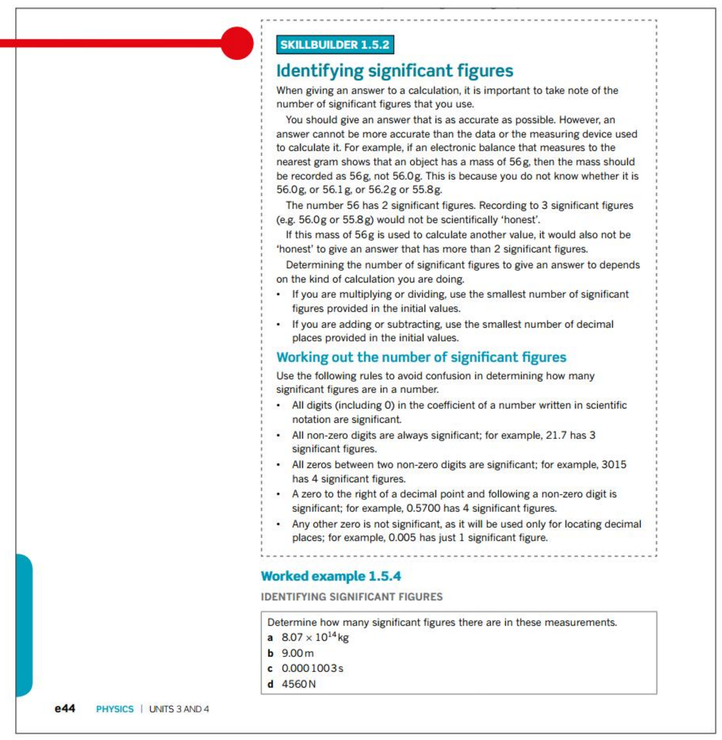
b Calculate the distance that the ball travels from the base of the cliff (that is, the range of the ball).

Thinking	Working
Write down the information relevant to the horizontal component of the motion. As the ball is hit horizontally, the initial speed gives the horizontal component of the velocity throughout the flight.	Horizontally: $u_x = 25.0\,\text{m s}^{-1}$, $t = 2.857\,\text{s}$ from part (a), $s_x = ?$

CHAPTER 2 | VECTORS AND PROJECTILE MOTION 21

Skillbuilders

Skillbuilders outline a method or technique. Each is instructive and self-contained. Skillbuilders step students through the skill to support science application required when analysing or utilising knowledge.



SKILLBUILDER 1.5.2

Identifying significant figures

When giving an answer to a calculation, it is important to take note of the number of significant figures that you use.

You should give an answer that is as accurate as possible. However, an answer cannot be more accurate than the data or the measuring device used to calculate it. For example, if an electronic balance that measures to the nearest gram shows that an object has a mass of 56 g, then the mass should be recorded as 56 g, not 56.0 g. This is because you do not know whether it is 56.0 g, or 56.1 g, or 56.2 g or 55.8 g.

The number 56 has 2 significant figures. Recording to 3 significant figures (e.g. 56.0 g or 55.8 g) would not be scientifically 'honest'.

If this mass of 56 g is used to calculate another value, it would also not be 'honest' to give an answer that has more than 2 significant figures.

Determining the number of significant figures to give an answer to depends on the kind of calculation you are doing.

- If you are multiplying or dividing, use the smallest number of significant figures provided in the initial values.
- If you are adding or subtracting, use the smallest number of decimal places provided in the initial values.

Working out the number of significant figures

Use the following rules to avoid confusion in determining how many significant figures are in a number.

- All digits (including 0) in the coefficient of a number written in scientific notation are significant.
- All non-zero digits are always significant; for example, 21.7 has 3 significant figures.
- All zeros between two non-zero digits are significant; for example, 3015 has 4 significant figures.
- A zero to the right of a decimal point and following a non-zero digit is significant; for example, 0.5700 has 4 significant figures.
- Any other zero is not significant, as it will be used only for locating decimal places; for example, 0.005 has just 1 significant figure.

Worked example 1.5.4

IDENTIFYING SIGNIFICANT FIGURES

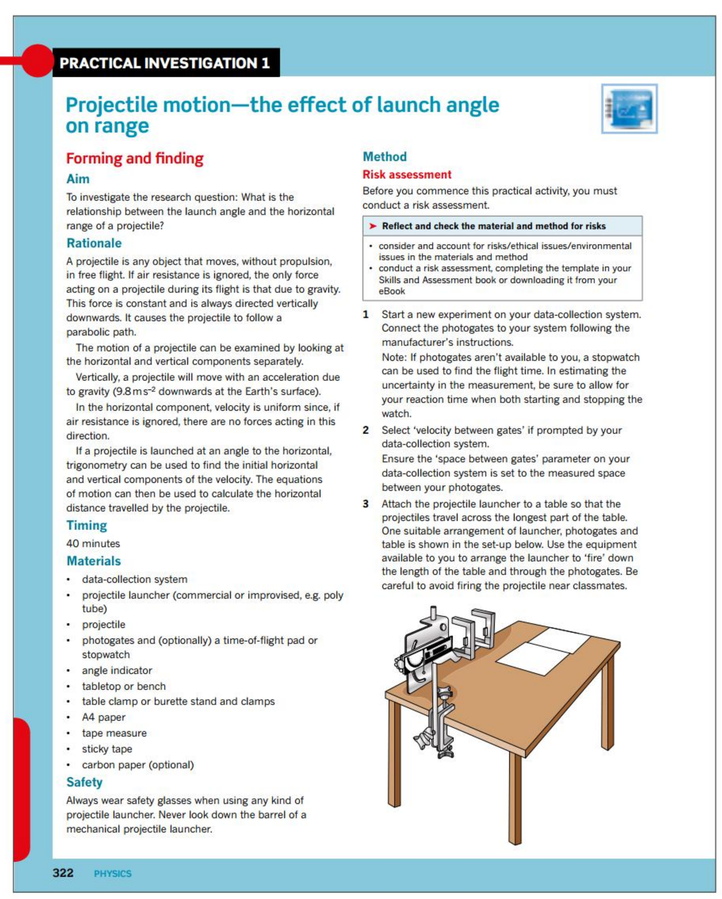
Determine how many significant figures there are in these measurements.

a 8.07×10^{14} kg
b 9.00 m
c 0.000 1003 s
d 4560 N

e44 PHYSICS | UNITS 3 AND 4

Practical manual

Practical investigations offer students the opportunity to develop, practise, and refine their Science inquiry skills. These activities involve gathering primary data to analyse and respond to scaffolded or open-ended science tasks, supporting deeper understanding and proficiency in scientific methods. Additionally, these tasks allow teachers to formatively assess students' Science inquiry skills and set students up well with the insights for Student experiment IA2, pertinent to Assessment objectives 1 to 6. All Practical investigations have been trialled and tested to ensure they can be safely performed and yield effective results. Full risk assessments and additional support are provided in the eBook.



PRACTICAL INVESTIGATION 1

Projectile motion—the effect of launch angle on range

Forming and finding

Aim

To investigate the research question: What is the relationship between the launch angle and the horizontal range of a projectile?

Rationale

A projectile is any object that moves, without propulsion, in free flight. If air resistance is ignored, the only force acting on a projectile during its flight is that due to gravity. This force is constant and is always directed vertically downwards. It causes the projectile to follow a parabolic path.

The motion of a projectile can be examined by looking at the horizontal and vertical components separately.

Vertically, a projectile will move with an acceleration due to gravity (9.8 m s^{-2} downwards at the Earth's surface).

In the horizontal component, velocity is uniform since, if air resistance is ignored, there are no forces acting in this direction.

If a projectile is launched at an angle to the horizontal, trigonometry can be used to find the initial horizontal and vertical components of the velocity. The equations of motion can then be used to calculate the horizontal distance travelled by the projectile.

Timing

40 minutes

Materials

- data-collection system
- projectile launcher (commercial or improvised, e.g. poly tube)
- projectile
- photogates and (optionally) a time-of-flight pad or stopwatch
- angle indicator
- tabletop or bench
- table clamp or burette stand and clamps
- A4 paper
- tape measure
- sticky tape
- carbon paper (optional)

Safety

Always wear safety glasses when using any kind of projectile launcher. Never look down the barrel of a mechanical projectile launcher.

Method

Risk assessment

Before you commence this practical activity, you must conduct a risk assessment.

➤ **Reflect and check the material and method for risks**

- consider and account for risks/ethical issues/environmental issues in the materials and method
- conduct a risk assessment, completing the template in your Skills and Assessment book or downloading it from your eBook

1 Start a new experiment on your data-collection system. Connect the photogates to your system following the manufacturer's instructions.
Note: If photogates aren't available to you, a stopwatch can be used to find the flight time. In estimating the uncertainty in the measurement, be sure to allow for your reaction time when both starting and stopping the watch.

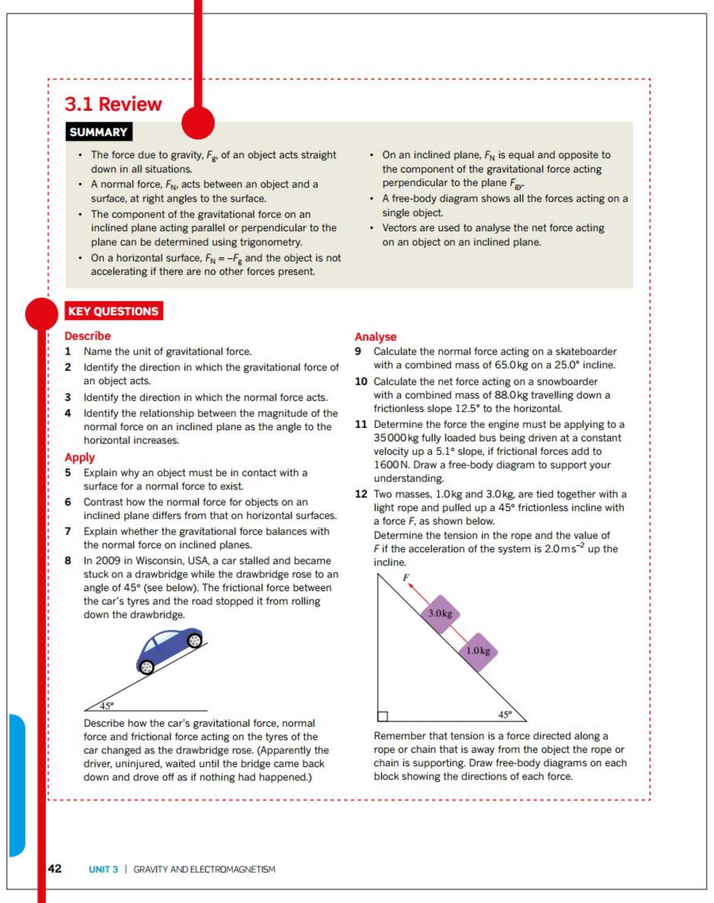
2 Select 'velocity between gates' if prompted by your data-collection system.
Ensure the 'space between gates' parameter on your data-collection system is set to the measured space between your photogates.

3 Attach the projectile launcher to a table so that the projectiles travel across the longest part of the table. One suitable arrangement of launcher, photogates and table is shown in the set-up below. Use the equipment available to you to arrange the launcher to 'fire' down the length of the table and through the photogates. Be careful to avoid firing the projectile near classmates.

322 PHYSICS

Module summary

Each module concludes with a summary to help students consolidate key points and concepts.



3.1 Review

SUMMARY

- The force due to gravity, F_g, of an object acts straight down in all situations.
- A normal force, F_N, acts between an object and a surface, at right angles to the surface.
- The component of the gravitational force on an inclined plane acting parallel or perpendicular to the plane can be determined using trigonometry.
- On a horizontal surface, $F_N = -F_g$ and the object is not accelerating if there are no other forces present.
- On an inclined plane, F_N is equal and opposite to the component of the gravitational force acting perpendicular to the plane $F_{\perp}$.
- A free-body diagram shows all the forces acting on a single object.
- Vectors are used to analyse the net force acting on an object on an inclined plane.

KEY QUESTIONS

Describe

1 Name the unit of gravitational force.
2 Identify the direction in which the gravitational force of an object acts.
3 Identify the direction in which the normal force acts.
4 Identify the relationship between the magnitude of the normal force on an inclined plane as the angle to the horizontal increases.

Apply

5 Explain why an object must be in contact with a surface for a normal force to exist.
6 Contrast how the normal force for objects on an inclined plane differs from that on horizontal surfaces.
7 Explain whether the gravitational force balances with the normal force on inclined planes.
8 In 2009 in Wisconsin, USA, a car stalled and became stuck on a drawbridge while the drawbridge rose to an angle of 45° (see below). The frictional force between the car's tyres and the road stopped it from rolling down the drawbridge.

Describe how the car's gravitational force, normal force and frictional force acting on the tyres of the car changed as the drawbridge rose. (Apparently the driver, uninjured, waited until the bridge came back down and drove off as if nothing had happened.)

Analyse

9 Calculate the normal force acting on a skateboarder with a combined mass of 65.0 kg on a 25.0° incline.
10 Calculate the net force acting on a snowboarder with a combined mass of 88.0 kg travelling down a frictionless slope 12.5° to the horizontal.
11 Determine the force the engine must be applying to a 35 000 kg fully loaded bus being driven at a constant velocity up a 5.1° slope, if frictional forces add to 1600 N. Draw a free-body diagram to support your understanding.
12 Two masses, 1.0 kg and 3.0 kg, are tied together with a light rope and pulled up a 45° frictionless incline with a force F, as shown below.
Determine the tension in the rope and the value of F if the acceleration of the system is 2.0 m s^{-2} up the incline.

Remember that tension is a force directed along a rope or chain that is away from the object the rope or chain is supporting. Draw free-body diagrams on each block showing the directions of each force.

42 UNIT 3 | GRAVITY AND ELECTROMAGNETISM

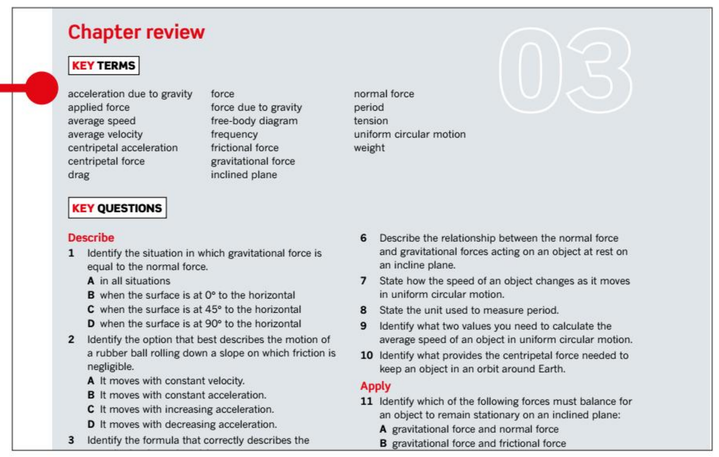
Module review

Key questions are provided to test students' understanding of concepts of the module. Questions are presented under the three Assessment objectives of Describe, Apply and Analyse. This structure allows students to demonstrate their progress in developing an understanding of the science subject matter.

How to use this book

Chapter review

Each chapter finishes with a list of key terms covered in the chapter, and a set of multiple choice and short response questions, reflecting the style and experience of the External Assessment (EA). These questions are organised under the four Assessment objectives for the subject matter: Describe, Apply, Analyse and Interpret.



Chapter review

03

KEY TERMS

acceleration due to gravity
applied force
average speed
average velocity
centripetal acceleration
centripetal force
drag
force
force due to gravity
free-body diagram
frequency
frictional force
gravitational force
inclined plane
normal force
period
tension
uniform circular motion
weight

KEY QUESTIONS

Describe

1 Identify the situation in which gravitational force is equal to the normal force.
A in all situations
B when the surface is at 0° to the horizontal
C when the surface is at 45° to the horizontal
D when the surface is at 90° to the horizontal

2 Identify the option that best describes the motion of a rubber ball rolling down a slope on which friction is negligible.
A It moves with constant velocity.
B It moves with constant acceleration.
C It moves with increasing acceleration.
D It moves with decreasing acceleration.

3 Identify the formula that correctly describes the

6 Describe the relationship between the normal force and gravitational forces acting on an object at rest on an incline plane.

7 State how the speed of an object changes as it moves in uniform circular motion.

8 State the unit used to measure period.

9 Identify what two values you need to calculate the average speed of an object in uniform circular motion.

10 Identify what provides the centripetal force needed to keep an object in an orbit around Earth.

Apply

11 Identify which of the following forces must balance for an object to remain stationary on an inclined plane:
A gravitational force and normal force
B gravitational force and frictional force

Icons

Go To icons make important links to relevant content within the student books in the course.

GO TO ➤

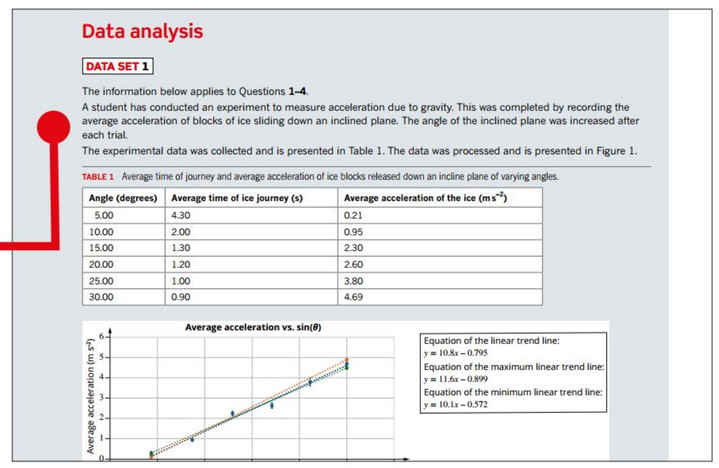
The Go To icons indicate:

- when a Practical investigation would be suitable to engage with
- where support is available for skills and assessment tasks in Chapter 1 of your eBook.

Every Practical investigation is supported by a complementary **SPARKlab** alternative practical.

Data analysis

Data analysis tasks at the end of most Chapter reviews provide an opportunity to respond to questions that use a range of qualitative and quantitative data relevant to that subject matter. The Data analysis tasks reflect the approach taken in the Data Test IA1 and align with the Assessment objectives 2, 3 and 4.



Data analysis

DATA SET 1

The information below applies to Questions **1–4**.
A student has conducted an experiment to measure acceleration due to gravity. This was completed by recording the average acceleration of blocks of ice sliding down an inclined plane. The angle of the inclined plane was increased after each trial.
The experimental data was collected and is presented in Table 1. The data was processed and is presented in Figure 1.

TABLE 1 Average time of journey and average acceleration of ice blocks released down an incline plane of varying angles.

Angle (degrees)	Average time of ice journey (s)	Average acceleration of the ice ($m\,s^{-2}$)
5.00	4.30	0.21
10.00	2.00	0.95
15.00	1.30	2.30
20.00	1.20	2.60
25.00	1.00	3.80
30.00	0.90	4.69

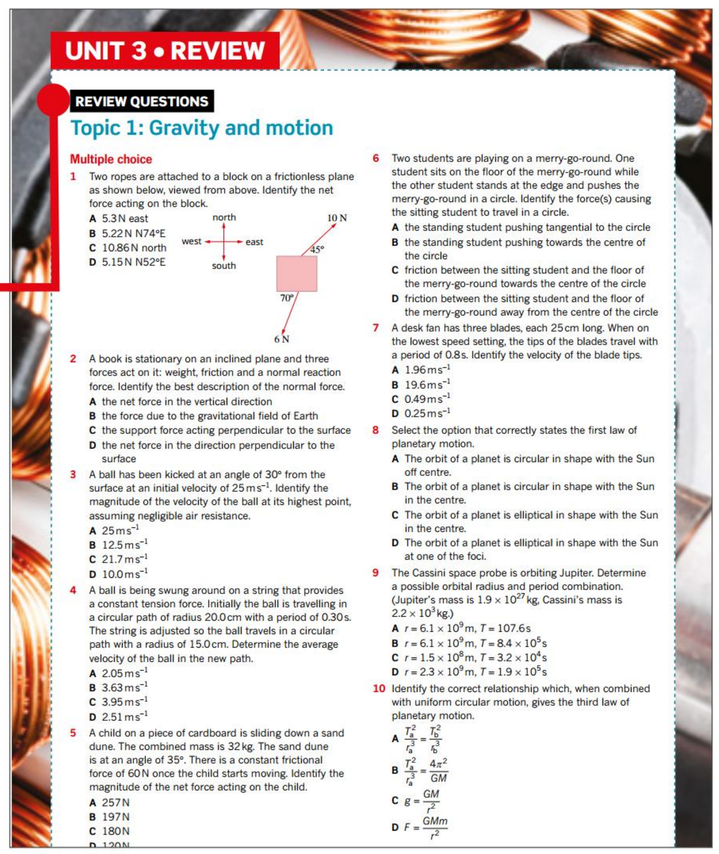
Average acceleration vs. sin(θ)

Average acceleration ($m\,s^{-2}$)

Equation of the linear trend line:
$y = 10.8x - 0.795$
Equation of the maximum linear trend line:
$y = 11.6x - 0.899$
Equation of the minimum linear trend line:
$y = 10.1x - 0.572$

Unit review

Each Unit finishes with a comprehensive set of exam-style questions, including multiple choice and short answer questions in the style of the External Assessment (EA). These review tasks assist students to draw together their knowledge and understanding of the whole unit.



UNIT 3 • REVIEW

REVIEW QUESTIONS

Topic 1: Gravity and motion

Multiple choice

1 Two ropes are attached to a block on a frictionless plane as shown below, viewed from above. Identify the net force acting on the block.
A 5.3 N east
B 5.22 N 74°E
C 10.86 N north
D 5.15 N 52°E

north, west, east, south; 10 N, 45°, 70°, 6 N

2 A book is stationary on an inclined plane and three forces act on it: weight, friction and a normal reaction force. Identify the best description of the normal force.
A the net force in the vertical direction
B the force due to the gravitational field of Earth
C the support force acting perpendicular to the surface
D the net force in the direction perpendicular to the surface

3 A ball has been kicked at an angle of 30° from the surface at an initial velocity of $25\,m\,s^{-1}$. Identify the magnitude of the velocity of the ball at its highest point, assuming negligible air resistance.
A $25\,m\,s^{-1}$
B $12.5\,m\,s^{-1}$
C $21.7\,m\,s^{-1}$
D $10.0\,m\,s^{-1}$

4 A ball is being swung around on a string that provides a constant tension force. Initially the ball is travelling in a circular path of radius 20.0 cm with a period of 0.30 s. The string is adjusted so the ball travels in a circular path with a radius of 15.0 cm. Determine the average velocity of the ball in the new path.
A $2.05\,m\,s^{-1}$
B $3.63\,m\,s^{-1}$
C $3.95\,m\,s^{-1}$
D $2.51\,m\,s^{-1}$

5 A child on a piece of cardboard is sliding down a sand dune. The combined mass is 32 kg. The sand dune is at an angle of 35°. There is a constant frictional force of 60 N once the child starts moving. Identify the magnitude of the net force acting on the child.
A 257 N
B 197 N
C 180 N
D 120 N

6 Two students are playing on a merry-go-round. One student sits on the floor of the merry-go-round while the other student stands at the edge and pushes the merry-go-round in a circle. Identify the force(s) causing the sitting student to travel in a circle.
A the standing student pushing tangential to the circle
B the standing student pushing towards the centre of the circle
C friction between the sitting student and the floor of the merry-go-round towards the centre of the circle
D friction between the sitting student and the floor of the merry-go-round away from the centre of the circle

7 A desk fan has three blades, each 25 cm long. When on the lowest speed setting, the tips of the blades travel with a period of 0.8 s. Identify the velocity of the blade tips.
A $1.96\,m\,s^{-1}$
B $19.6\,m\,s^{-1}$
C $0.49\,m\,s^{-1}$
D $0.25\,m\,s^{-1}$

8 Select the option that correctly states the first law of planetary motion.
A The orbit of a planet is circular in shape with the Sun off centre.
B The orbit of a planet is circular in shape with the Sun in the centre.
C The orbit of a planet is elliptical in shape with the Sun in the centre.
D The orbit of a planet is elliptical in shape with the Sun at one of the foci.

9 The Cassini space probe is orbiting Jupiter. Determine a possible orbital radius and period combination. (Jupiter's mass is 1.9×10^{27} kg, Cassini's mass is 2.2×10^{3} kg.)
A $r = 6.1 \times 10^{9}$ m, $T = 107.6$ s
B $r = 6.1 \times 10^{9}$ m, $T = 8.4 \times 10^{5}$ s
C $r = 1.5 \times 10^{8}$ m, $T = 3.2 \times 10^{4}$ s
D $r = 2.3 \times 10^{9}$ m, $T = 1.9 \times 10^{5}$ s

10 Identify the correct relationship which, when combined with uniform circular motion, gives the third law of planetary motion.
A $\frac{T_a^2}{r_a^3} = \frac{T_b^2}{r_b^3}$
B $\frac{T_a^2}{r_a^3} = \frac{4\pi^2}{GM}$
C $g = \frac{GM}{r^2}$
D $F = \frac{GMm}{r^2}$

Glossary

Key terms are shown in **bold** throughout the Student Book and are listed at the end of each chapter. A comprehensive glossary at the end of the book defines all the key terms and the glossary aligns with the syllabus context.

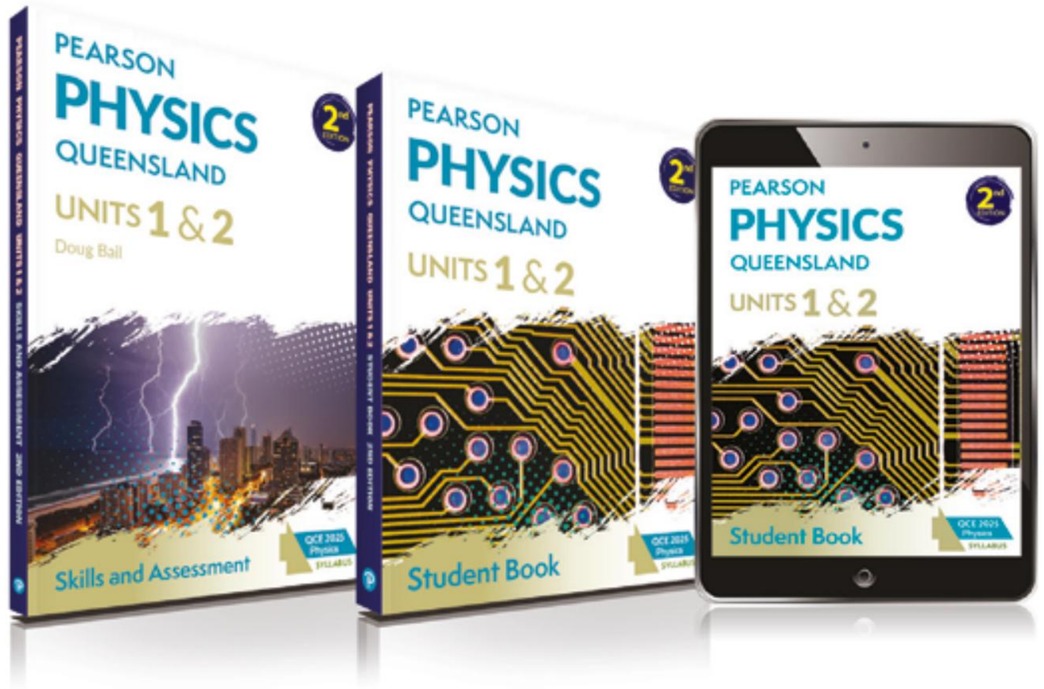
Answers

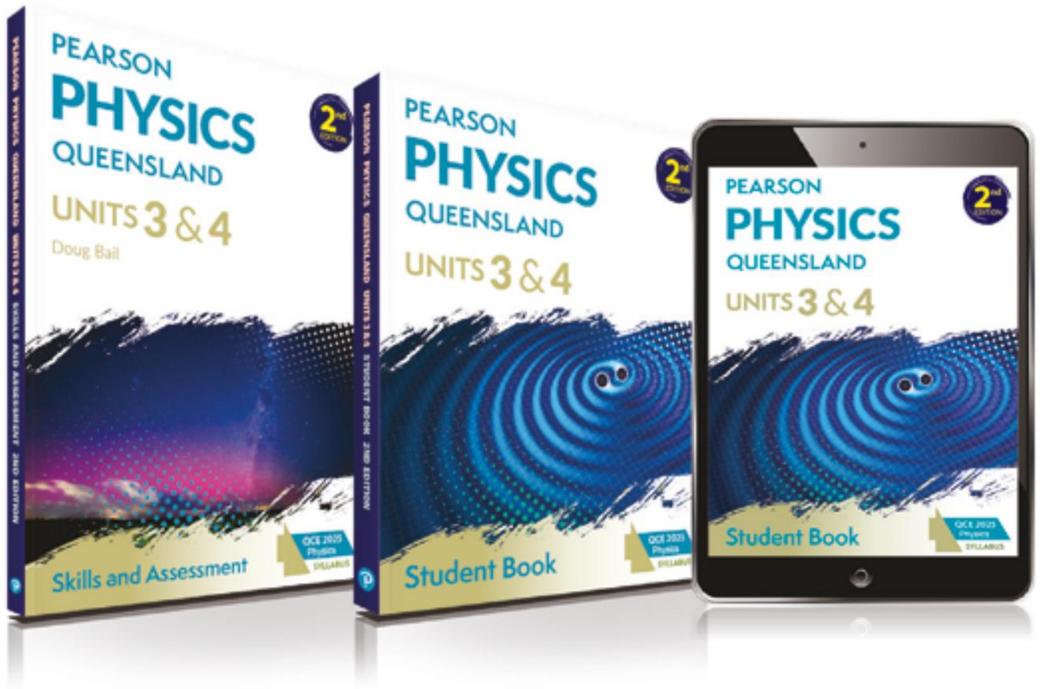
Comprehensive answers and fully worked solutions for all Module review tasks, Try yourself, Science as a human endeavour, Chapter reviews and Unit reviews are provided via the eBook.

Pearson

Pearson Physics Queensland Units 3 & 4 2nd edition

Trusted throughout Queensland to provide high quality support for implementation of the QCE Physics 2025 Syllabus, **Pearson Physics Queensland 2nd edition** has been refined to include what is needed to cover the QCE outcomes.





Student book

- The expert author team has delivered the same high-quality content you can trust, in the streamlined new edition for Queensland science classrooms.
- New, enhanced, and updated features that make the new second edition Student Books stand out:
  - New Science as a Human Endeavour sections
  - New Data Analysis tasks at the end of each Chapter review
  - Enhanced and updated Skills and Assessment Toolkit
  - Enhanced question sets
  - Updated Practical Manual of Practical Investigations
  - Updated Unit reviews and glossary.

Skills and assessment book

- The Skills and Assessment Book gives students the edge in preparing for all forms of assessment.
- It has been updated and refined to respond to the revised syllabus, and specifically provide opportunities to consolidate, develop and apply subject matter and Science inquiry skills. This resource features:
  - An updated Toolkit
  - Key knowledge summaries
  - Worksheets
  - Practical investigations and guidance
  - Assessment practice
  - QCAA exam and exam-style questions for each topic.

eBook

Learner eBook access includes:

- Student book content
- Access to digital resources
- Fully worked solutions.

Teacher eBook access includes:

- Access to everything learners have access to
- Practical investigation expected results, common mistakes, suggested answers and full safety notes and risk assessments
- Teaching, learning and assessment programs
- Syllabus mapping documents.

Find out more and explore the series at

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CHAPTER

01 Physics skills and assessment toolkit

This chapter provides important information and support in the study of the QCAA General Senior Syllabus for Physics.

The Physics skills and assessment toolkit is designed to be used as a reference tool. It should be consulted on a need-to-know basis, where relevant, during this course of study. It is not intended that this chapter be worked through as a whole.

This chapter focuses on providing support and guidance in:

- **Development and application of scientific skills**
  - mathematical and statistical processes used in physics
  - SI units
  - visual representations
  - graphical representations
  - measurement errors and uncertainty.
- **Completing the assessment tasks**
  - Data test (Internal Assessment IA1)
    - preparation in skill development.
  - Student experiment (Internal Assessment IA2)
    - forming a relevant research question
    - justifying experiment modifications
    - developing a methodology
    - finding sufficient, relevant data
    - interpreting and analysing evidence
    - evaluating experimental process
    - scientific writing and representations
    - referencing sources
  - Research investigation (Internal Assessment IA3)
    - developing a research question from a claim
    - collecting relevant and sufficient evidence to answer research question
    - identifying and analysing trends, patterns, relationships in the evidence
    - evaluating the quality and limitations of the evidence
    - evaluating the research process
    - scientific writing and representations
    - referencing sources
  - Examination (External Assessment)
    - understanding the features and conditions of the two exam papers
    - strategies to apply throughout the course to enhance learning
    - strategies for revising and consolidating learning
    - techniques and hints for sitting the exam.

Chapter organisation

The chapter is arranged in four parts:

- Part A: Working scientifically
- Part B: Student experiment
- Part C: Research investigation
- Part D: Examination.

An outline of these parts is provided below.

QCAA Physics Syllabus objectives

- describe ideas and findings
- apply understanding
- analyse data
- interpret evidence
- evaluate conclusions, claims and processes
- investigate phenomena

Physics General Senior Syllabus 2025, © State of Queensland (QCAA) 2024

Part A: Working scientifically

Part A focuses on basic mathematical skills and their applications. It features many Worked examples and opportunities to apply these examples yourself. These skills are assessed, directly and indirectly, in assessment tasks and to analyse data in practical investigations. Part A focuses on skills for the Data test, and experiments. These skills are useful when completing sections of the Student experiment, Research investigation and the Examination.

Refer to the following outline of *Part A: Working scientifically*, to learn, revise and practise the skills in the areas in which you need help.

Module	Look here for	eBook page
1.1 Physics	- areas of physics - the work of scientific research	e7
1.2 Orders of magnitude	- scientific notation - transforming decimal notations to scientific notation - converting between scientific notation and scientific units, orders of magnitude and prefixes - SI prefixes - examples of calculations	e14
1.3 Mathematical basics for physics	- examples of maths used in physics - analysing straight-line graphs - trigonometric ratios and logarithms	e20
1.4 Units	- measurement and units - correct use of unit symbols - unit conversions	e28
1.5 Uncertainty and error	- explanations of the terms *uncertainty*, *error*, *accuracy* and *precision* - causes of errors - calculations with uncertainty and error - writing measurements with uncertainty and error values - writing measurements and calculations to the correct significant figure - determining the absolute uncertainty of a value - converting between absolute and percentage uncertainties - calculating a value along with the associated uncertainty	e33
1.6 Tables and graphing	- arranging and recording data in tables - converting data from tables to graphs - types of graphs - outliers and how they are represented on graphs - representing missing data on graphs	e50
1.7 Data analysis	- calculating mean, median, mode and range - regression, linear regression, coefficient of determination and *r*-values - linearising data - three line graphs	e58
1.8 Scientific writing	- writing scientifically - developing scientific representations - maintaining a science journal - referencing sources - in-text citations - using AI in research and writing - plagiarism - referencing AI sources - multimodal presentations	e72

Part B: Student experiment (IA2)

Part B focuses on the student experiment. This internal assessment task requires students to follow the full scientific method over an extended and defined period of time. Students develop their own research question to investigate, based on an identified experiment related to Unit 3 subject matter.

Part B supports you through all aspects of the student experiment. The QCAA objectives and instrument-specific marking guide (ISMG) for the assessment are explained.

Part B provides examples of how to **modify** (**extend**, **refine** or **redirect**) the initial experiment to write an experimental research question. Included is a step-by-step guide to evaluate the quality of your question and explanations of scientific methodology. Part B also covers data types, data collection and analysis of data to draw valid conclusions, including how to evaluate the quality of data including its reliability and validity, and how to link these to logical improvements and extensions. Also provided is support in writing-up your scientific report, covering writing conventions and referencing sources.

Refer to the following outline of *Part B: Student experiment*, to learn, revise and practise your skills in the areas in which you need help.

Module	Look here for	eBook page
1.9 Syllabus requirements	- instrument-specific marking guide (ISMG) - assessment objectives - suggested report structure - length requirements	e83
1.10 Forming	- establishing background information - developing a rationale - defining variables - developing the research question - evaluating the research question - justifying the question modification - putting it all together: sample report	e86
1.11 Finding	- determining the risk assessment - managing risk - considering environmental and ethical issues - collecting sufficient and relevant raw data - collecting data electronically - putting it all together: sample report	e95
1.12 Analysing	- presenting the data - processing data using mathematical techniques - identifying patterns, relationships, trends in data - interpreting results - identifying uncertainty and limitations in the evidence - putting it all together: sample report	e105
1.13 Interpreting and evaluating	- drawing a conclusion that is linked to the research question - discussing reliability and validity - identifying improvements and extensions to the research - putting it all together: sample report	e112

Part C: Research investigation (IA3)

Part C focuses on the research investigation. This internal assessment task requires students to gather secondary evidence on a research question. It is completed over an extended and defined period of time. Students develop their own research question to investigate, based on a claim related to Unit 4 subject matter.

Part C supports you through all aspects of the research investigation. The QCAA objectives and instrument-specific marking guide (ISMG) for the assessment are explained.

Part C assists with writing your research question. It considers examples of claims, and how to analyse claims for context and guides you in developing your own research question. You will be guided in writing a specific and relevant research question that encompasses a small sub-section of the claim and is linked to Physics syllabus concepts. You will consider the information on locating and evaluating suitable secondary sources for the research, including identifying errors and relationships in data, and assessing validity. You will learn how to formulate a justified conclusion, and describe improvements and extensions. There is support for writing your scientific report, including guidance on scientific writing style and the structure of the report.

Refer to the following outline of *Part C: Research investigation*, to learn, revise and practise your skills in the areas in which you need help.

Module	Look here for	eBook page
1.14 Syllabus requirements	- instrument-specific marking guide (ISMG) - assessment objectives - suggested report structure - length requirements	e117
1.15 Forming and finding	- analyse a claim - identify variables and measurable terms in the claim - examples of claims and research questions developed from them - guidelines for developing a question - develop a research question - refining a research question - putting it all together: sample report	e119
1.16 Analysing	- collecting sufficient and relevant evidence - identifying trends, patterns, relationships in the evidence - assessing limitations of the evidence - putting it all together: sample report	e131
1.17 Interpreting	- assessing if the evidence justifies the claim - presenting an argument whether the claim is justified - reaching a conclusion about the claim - putting it all together: sample report	e136
1.18 Evaluating	- evaluating the quality of the evidence - suggesting any extrapolations of the claim - suggesting any improvements/extensions to the investigation - putting it all together: sample report	e138

Part D: Examination (External Assessment)

Part D focuses on the examination, a summative external assessment (EA). The examination requires students to complete two 90-minute papers containing multiple choice and short answer questions. Each paper covers the whole physics course relating to Units 3 and 4. The examination constitutes 50% of the total assessment for the course.

Refer to this section early in the year, not just in the weeks before the examination. Effective exam preparation needs ongoing consolidation of learning and revision of course material at regular intervals. Effective preparation begins with a sound understanding of the course and its requirements. It is also important that you know where you can go for support and what sort of support is available to you through the course.

The examination requires that you use skills and strategies that are not necessarily used in the student experiment and research investigation. The internal data test and external examination are similar in the strategies you should apply to complete them. There is possibly more anxiety felt by students regarding the examination, as it accounts for 50% of the total mark in physics. However, good preparation will see you entering the exam with confidence.

Part D guides you through all aspects of preparation for the examination. Refer to it to get tips on strategies to help you consolidate your learning, and for revision hints and suggestions. Before completing practice exams, read through the list of strategies to use during perusal (reading) time and writing time. Apply these strategies as you answer each practice paper. Be aware that past exam papers from 2020–2024 relate to the Senior Physics 2019 Syllabus, so use your second edition textbook to identify topics and questions which are no longer relevant to the 2025 Syllabus. Conversely, special attention needs to be paid to revision of topics that have been added to the 2025 Syllabus. Revision questions for new topics are provided in the second edition textbook. Your teacher will also provide advice about the correct use of past exam papers.

Sitting the exam is more than having an understanding of subject matter and possessing scientific skills. It is also about exam technique, as this can boost your performance.

Refer to the following outline of Part D: Examination as needed throughout the year to learn about strategies and techniques to enhance your learning, revision and examination performance.

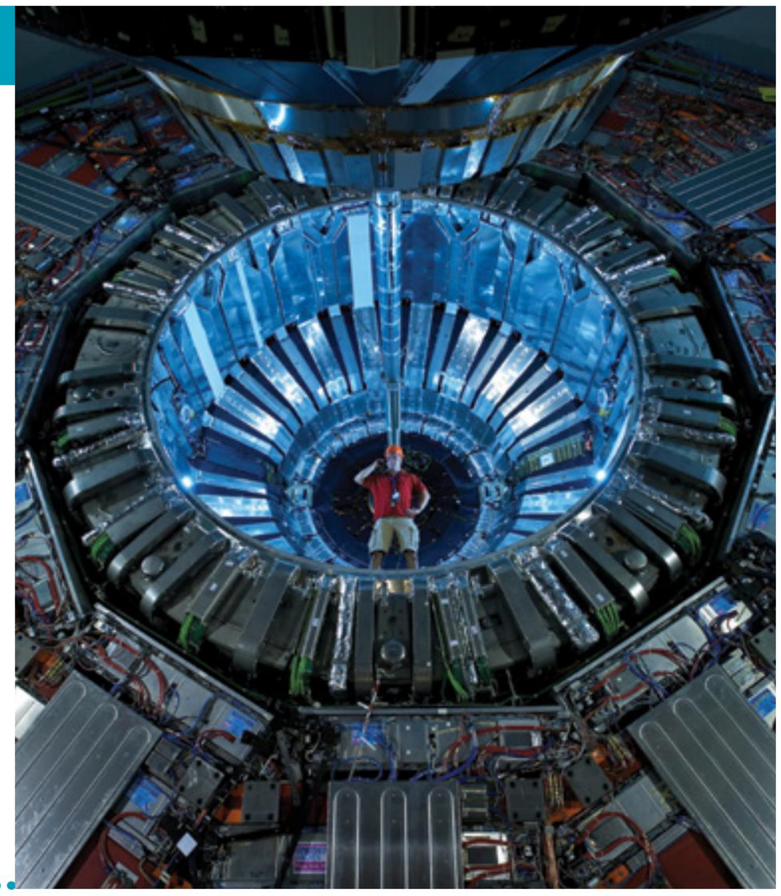
Module	Look here for	eBook page
1.19 Examination preparation	- overview of the two papers (duration, content, response items and equipment) - strategies for consolidating learning - strategies for revising and practising - strategies for sitting the exam	e145

GO TO ➤ your eBook to access Chapter 1 Physics Skills and Assessment Toolkit

1.1 Physics

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- understand and appreciate that physics is a fundamental science, and its capacity to ask the 'big' questions makes it incredibly interesting
- understand that science provides a systematic approach for comprehending the world.
- explain the difference between scientific models, theories, laws, principles and facts
- understand that physics uses natural laws, theories, models and principles to describe real phenomena
- appreciate that physics uses mathematics
- recall the major areas of physics
- explain how a vast number of professions use some aspect of physics
- appreciate that physics is a dynamic and evolving branch of science, and that not every problem has been solved.



WHAT IS PHYSICS?

Science is a human endeavour to understand the world and the known universe. It is one method of many used to develop knowledge. This knowledge is continually refined and redefined. Science follows a **methodology** to observe, test, measure, analyse and evaluate natural **phenomena** in a way humans can understand and construct meaning. There is no single **scientific method**; however, it is a cyclical process including observation of natural phenomena, questioning, hypothesising and predicting, experimentation and gathering **data**, refining and altering all previous elements, and theorising.

Today, all scientific disciplines are expanding into new frontiers. The number of divisions and fields in physics is ever-increasing, and the relationship between disciplines is becoming more intertwined. Innovations today are crossing the traditional barriers between technology, chemistry, physics and biology of the past 100 or so years.

Physics is the study of motion, forces and energy. It is the most **fundamental** science. It deals with the laws, theories and principles governing force, energy and motion across all imaginable scales throughout the universe. These range from the interactions between particles that make up the individual protons and neutrons inside every atomic nucleus, to the motions of galaxies that comprise the universe itself. Physics is full of history and amazing discoveries and famous scientists, such as the scientists in Figure 1.1.1, who made numerous contributions to modern physics.

FIGURE 1.1.1 The fifth Solvay conference held in 1927 was perhaps the greatest convergence of physicists and chemists in the 20th century. Back row: Piccard, Henriot, Ehrenfest, Herzen, De Donder, Schrödinger, Verschaffelt, Pauli, Heisenberg, Fowler, Brillouin. Centre row: Debye, Knudsen, Bragg, Kramers, Dirac, Compton, de Broglie, Born, Bohr. Front row: Langmuir, Planck, Curie, Lorentz, Einstein, Langevin, Guye, Wilson, Richardson.

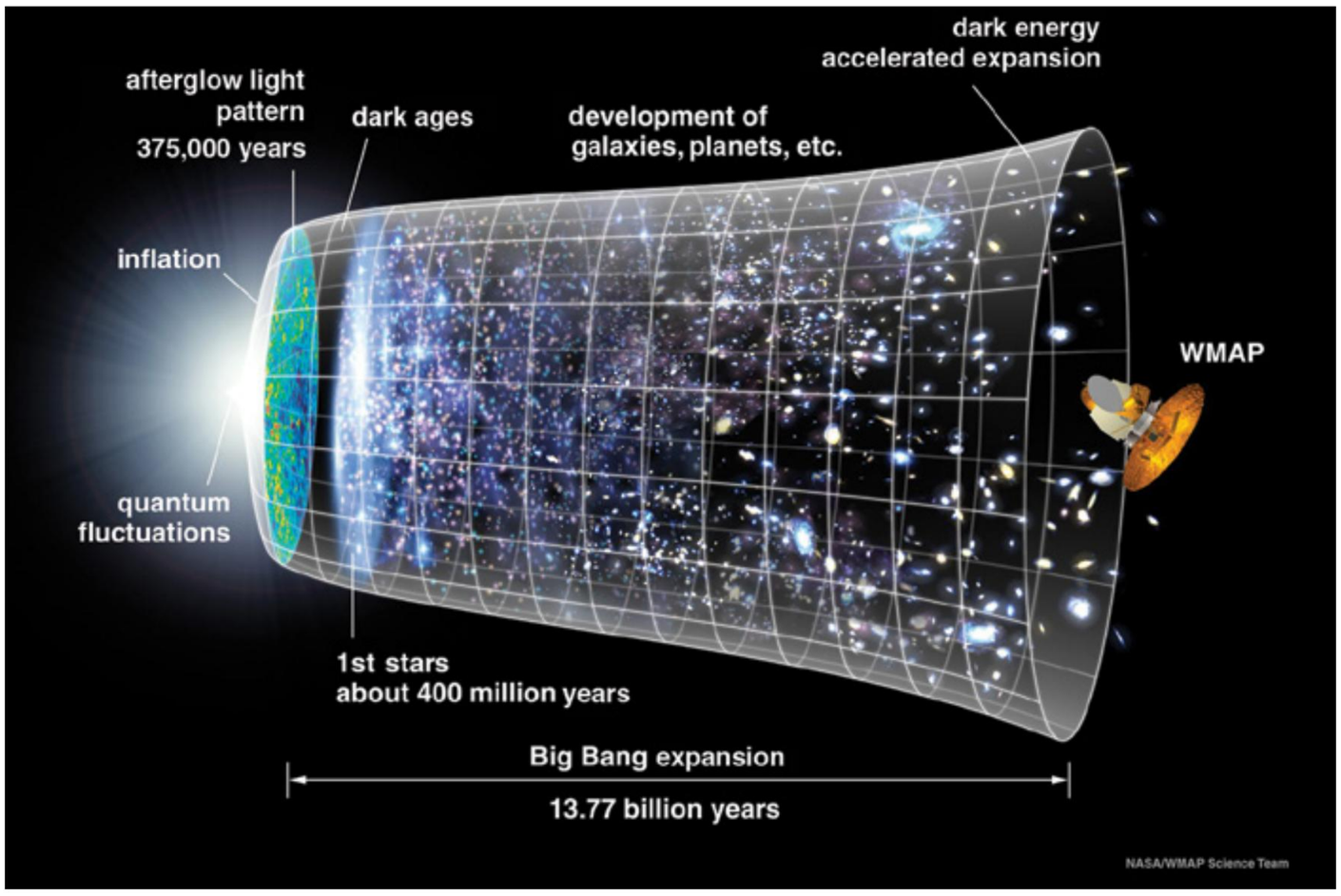


FIGURE 1.1.2 Fourteen billion years of history of the universe. The Big Bang theory for the creation of the universe is shown on the far left. The present-day universe is on the far right, along with a satellite called the Wilkinson Microwave Anisotropy Probe (WMAP), which collected data to help piece together the theory.

FIGURE 1.1.3 An artist's illustration of a planet being destroyed as it orbits a very strange star in our galaxy called 'Tabby's Star'. The light from this star appears to randomly fluctuate and currently defies all known explanations. The latest theory is that it is likely due to an uneven dust cloud moving around the planet.

The wonder of physics lies in its ability to ask the 'big' questions, such as:

- Where did the universe come from? To date, our best theory is the Big Bang theory (Figure 1.1.2).
- Does the universe have an end?
- Are we alone in the universe, or is the universe full of intelligent, alien civilisations (Figure 1.1.3)?
- What is matter made up of?
- Is there a single theory or equation that can describe everything?

Interestingly, the answers to these questions are still unknown, but perhaps you will be inspired to try to answer them.

Physics uses the language of mathematics to make logical sense of the universe, using models and theories to explain natural phenomena. If it is not supported by observations and experiments, then the model or theory is rejected and a new theory takes its place.

If a ladder showing the level of fundamental explanations of the natural world is made, as in Figure 1.1.4, physics would be on the second-bottom rung, second only behind mathematics in the way it can describe the basic interactions in the natural world.

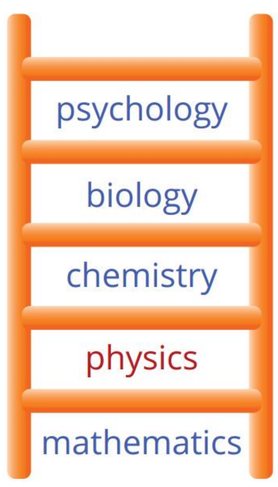


FIGURE 1.1.4 Physics uses mathematics to explain how the natural world works. Chemistry uses the laws of physics to explain matter and the interactions of matter, whereas biology and psychology use the products of chemical reactions to explain the living world.

All other sciences have their basis in some aspect of physics. For example, an understanding of how chemical bonding works can be explained by the laws of electrostatic forces and the theory of quantum mechanics.

Physics had its origins more than 5000 years ago when the ancient Babylonians recorded the positions of stars, planets and comets, so it is generally considered that astronomy (a major branch of physics) is the oldest science. In the 21st century, physics is used in almost every aspect of science. One of the newest branches of physics is gravitational wave astrophysics, which originated with Albert Einstein in 1916 and was only confirmed with data in 2016.

Since Einstein's time, physicists have refined their understanding of the universe. Most of the time, physicists have used that body of knowledge to improve the lives of humans and the other organisms that share this planet.

DOMAINS AND BRANCHES OF PHYSICS

Physics can be roughly divided into four domains, depending on the size of the objects that are interacting and how fast they travel (Figure 1.1.5). Each domain has several branches stemming from historical advances in thinking or in experimental results.

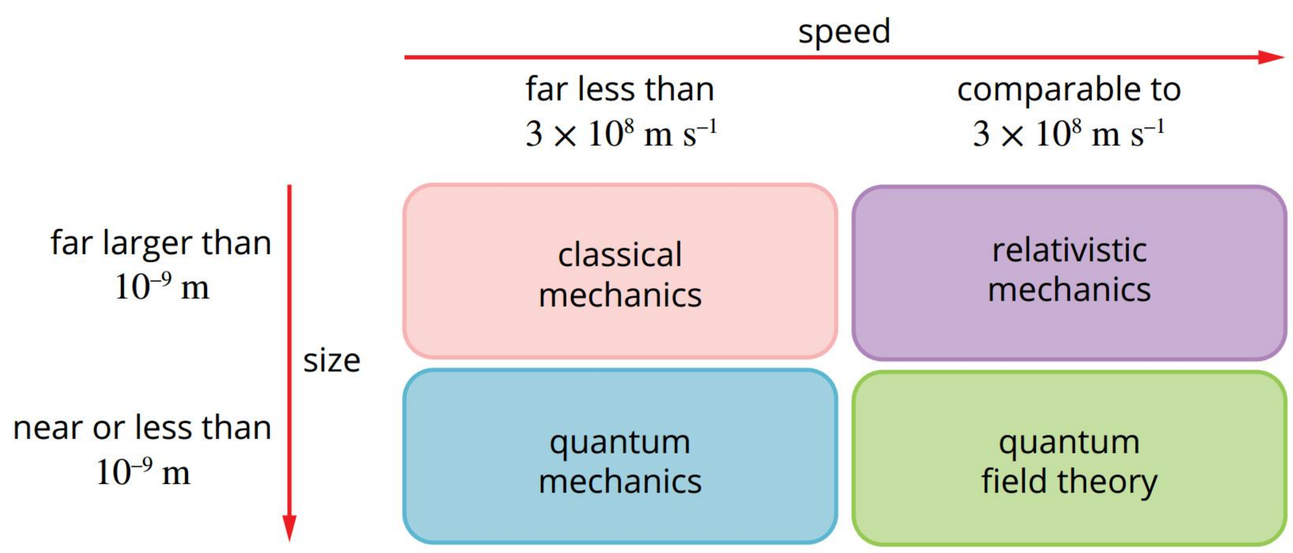


FIGURE 1.1.5 The four domains of physics describe matter and energy of various sizes moving at various speeds.

Classical mechanics is the first domain of physics. It deals with the forces, energy, gravity and motion of everyday objects, planets, stars and galaxies as long as they are not moving at close to the speed of light. Most of the physics you will study in Years 11 and 12 comes from classical mechanics, or the view of the universe given to us by Isaac Newton from the 17th century.

Quantum mechanics is the second domain of physics. In Units 3 and 4 you will touch on the 'modern' view of physics by exploring quantum mechanics, or the strange world of light and very small particles, such as the atom and its constituents. Physicists formulated these theories in the early 20th century. Quantum mechanics has been described as the most accurate and precise scientific theory ever written, but it does not include gravity in its formulation.

Relativistic mechanics is the third domain of physics. In Units 3 and 4 you will explore part of the bizarre and counterintuitive world of relativistic mechanics brought to us by Albert Einstein also at the beginning of the 20th century. Relativistic mechanics deals with the motion, gravity and energies of all objects larger than an atom when they travel at speeds approaching the speed of light.

Quantum field theory (QFT) is the fourth domain of physics. It is a combination of the theories of the very small (quantum mechanics) and very fast (relativistic mechanics). The mathematics of QFT is beyond high school level and you will not explore this in any detail.

To date, nobody has come up with a successful unification or grand unified theory (GUT) of these four aspects of physics. The GUT would have to describe the entire universe at every scale and speed, and make measurable predictions that can be tested with experiments. In other words, the physics of very small objects moving very fast under gravity is yet to be understood. For example, at the very centre of a black hole, known as the singularity, the laws of physics break down because we do not yet understand how small particles behave under the influence of strong gravity.

String theory describes everything in the universe as a tiny vibrating string of energy (Figure 1.1.6.) It is a possible GUT, but so far has not been used to make measurable predictions.

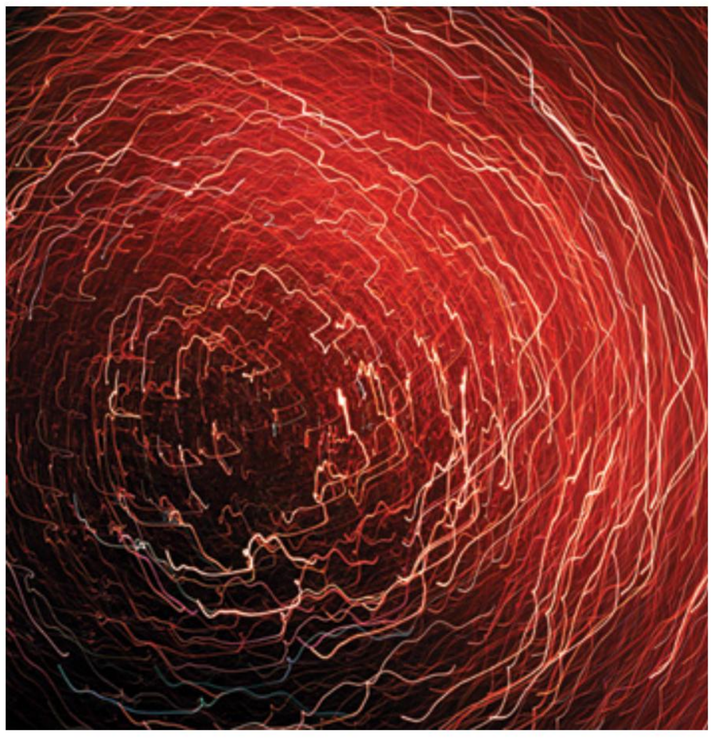


FIGURE 1.1.6 String theory describes everything in the universe as a tiny, vibrating string whose frequency determines if the object is a particle of matter or a wave of energy.

The major branches of physics are mechanics, thermodynamics, atomic and nuclear physics, electromagnetism, waves and relativity.

Using the four domains of physics, Figure 1.1.7 shows all of the branches of physics you will study in this course. These branches are briefly explained in Table 1.1.1, which also lists some of the famous people who worked in them.

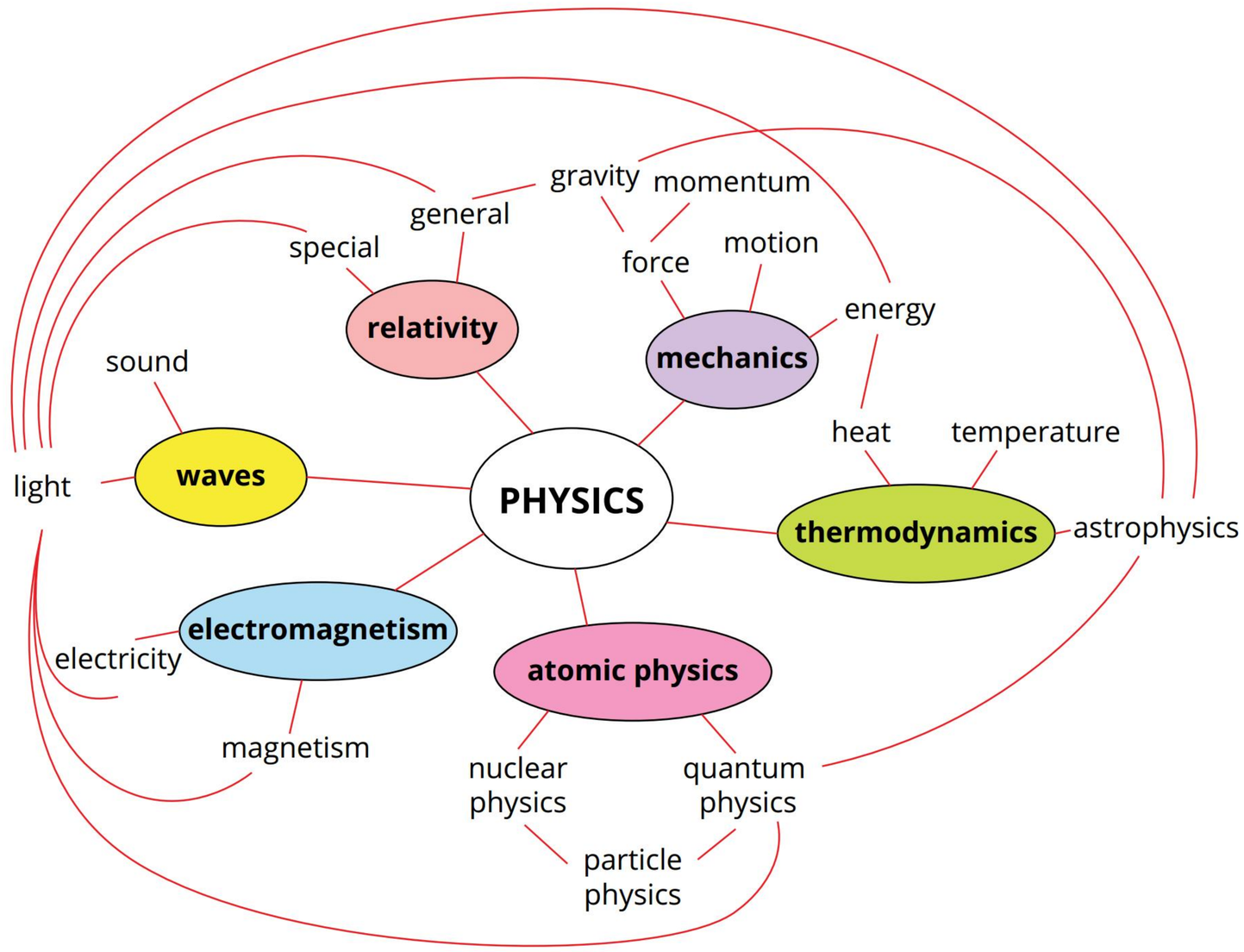


FIGURE 1.1.7 This non-exhaustive concept map shows the branches of physics and the links between their concepts.

TABLE 1.1.1 A brief description of the branches of physics

Branch of physics	What it explains	Famous people involved in the branch
mechanics	motion, forces, gravity and energy	Isaac Newton, Galileo, Nicolas Copernicus, Johannes Kepler, Robert Hooke, Blaise Pascal
thermodynamics	temperature, heat, matter, and the combination of these to provide motion	James Joule, Ludwig Boltzmann, Sadi Carnot, Felix Wankel, Rudolf Diesel
waves	sound, light and how energy moves from one location to another	Isaac Newton, Max Planck, Christiaan Huygens, Christian Doppler, Heinrich Hertz
electromagnetism	electricity, current, voltage and magnets, motors and generating electrical power	James Clerk Maxwell, Michael Faraday, Nikolai Tesla, Andre-Marie Ampere
atomic and nuclear physics	the atom, nucleus, particles that make up the nucleus, and how they interact with other matter and light	Marie Curie, Albert Einstein, Niels Bohr, Ernest Rutherford, Max Planck, Stephen Hawking, Richard Feynman, Peter Higgs
relativity	how the laws of physics above change when particles move very fast or when particles become close to a very large but dense object	Albert Einstein, Galileo, Hendrik Lorentz

THE ROLE AND WORK OF A PHYSICIST

Those who study physics are typically known as physicists. Physicists use models, theories and laws to explain the universe in terms of mathematical symbols. To check and refine their theories, they carry out experiments, collect data and analyse their results. Their theories are then changed or refined according to their results. The foundation of all sciences, including physics, is scientific research. Scientific research works in the unknown to develop new understandings. To build evidence, it may take years and many experiments. In interpreting scientific evidence, scientists endeavour to establish **models**, **theories**, **laws**, **principles** and **facts**. These are illustrated in Figure 1.1.8. It is important to note that all these deductions change over time as knowledge develops.

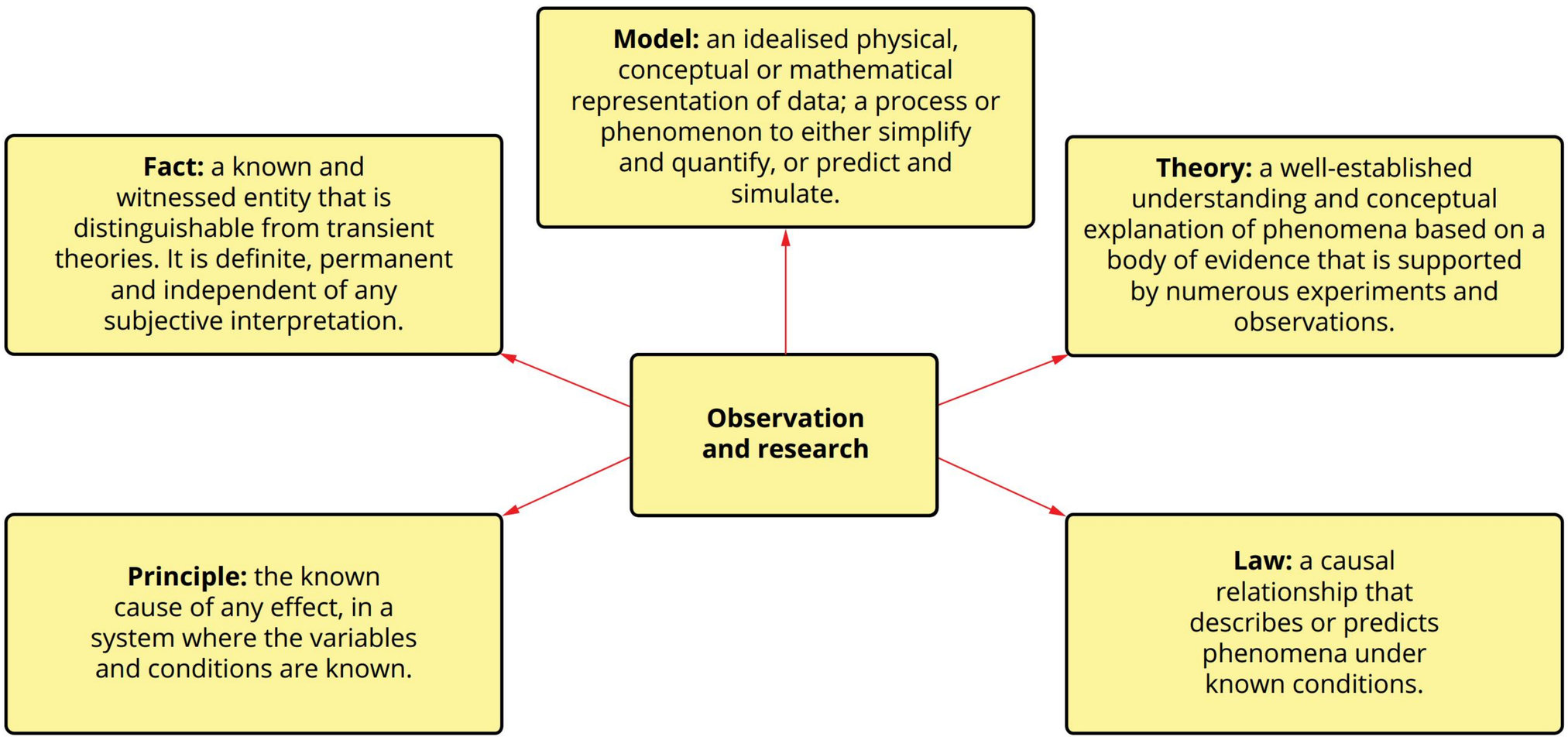


FIGURE 1.1.8 Scientific research and observations are used to develop facts, principles, laws, theories and models.

A physics model is a way of visualising a particular physical phenomenon that is quite often impossible to imagine in the real world. It may or may not be entirely correct.

Examples of models:

- the wave model of light
- the particle model of light.

A physics theory is a model that is more mathematically rigorous. It uses mathematical formulas to predict the behaviour of the model. Again, it may or may not be correct, but the phenomenon it describes is real.

Examples of theories:

- Newton's theory of gravity
- Einstein's general theory of relativity.

A physical law is a general statement that is found to be experimentally true over a large range of observed phenomena. It describes how nature behaves. A principle is a law but is more specific in its scope.

Examples of laws:

- The three laws of motion
- Archimedes' principle.

Physics uses mathematics to explain the natural world in terms of models, theories, laws and principles.

The advances in scientific endeavours as well as innovations have seen a significant increase in multiple scientific specialities and disciplines working together. When more than one discipline is required to solve a problem or develop an innovation, it is said to be transdisciplinary. Transdisciplinary approaches to scientific endeavours form the heart of STEM.

As the world changes, science, technology, engineering and maths (STEM) integrate numerous disciplines into vocational roles. There are numerous reports every year outlining that most future professions will be STEM related. For example, a recent report from a multinational business organisation indicated that jobs in 75% of growing and future industries will require STEM qualifications.

A STEM qualification fosters skills in areas such as creativity and critical thinking, and is highly regarded in public and private businesses.

Physics is the most fundamental science and explains how the laws of nature work, so anyone that uses technology is using some aspect of physics. Examples of some of the many occupations that use physics either directly or indirectly are given in Table 1.1.2 and Figures 1.1.9 to 1.1.11.

TABLE 1.1.2 Examples of the branches of physics used in various professions

Profession	Aspect of physics used
archaeologists	nuclear physics used in carbon dating
astronomers	all aspects of relativity, light and gravity
climate scientists	forces, thermodynamics
dentists	forces, thermodynamics, sound and light
doctors	forces, nuclear physics, atomic physics, waves, electromagnetism (see Figure 1.1.9)
electricians	electromagnetism
engineers (civil, mechanical, electrical, sound, optical, aerospace, materials, mining)	all aspects of physics
geologists	gravity, thermodynamics, atomic physics

FIGURE 1.1.9 A medical physicist prepares a patient for a scan in a magnetic resonance imaging (MRI) machine.

FIGURE 1.1.10 Police use physics to determine the speed and direction of vehicles involved in traffic accidents.

FIGURE 1.1.11 Physics plays a central role in the animation of many video games and developers need to know the laws of physics to accurately represent motion in their games.

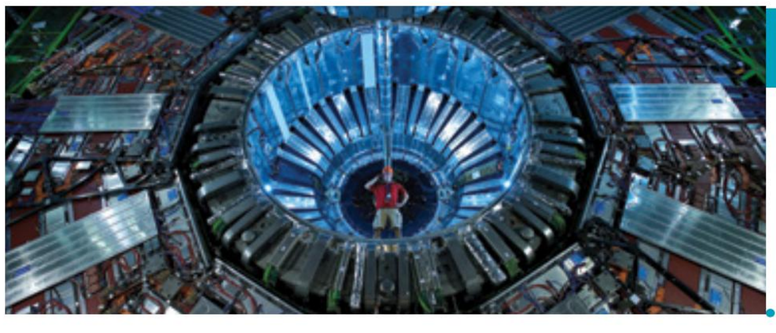
1.1 Review

SUMMARY

- Science is a systematic approach to develop knowledge through testable explanations and repeatable means.
- Physics is a dynamic and evolving branch of science.
- Physics uses mathematics as its language.
- A physics model is a visual way of describing an invisible natural phenomenon.
- A physics theory is a mathematical description of a natural phenomenon.
- A law of physics is a general statement that is found to be experimentally true over a large range of observations.
- A physics principle is a law of physics that is more specific in its context.
- Classical mechanics, quantum mechanics, relativistic mechanics, and quantum field theory are the four domains of physics.
- Major branches of physics are mechanics, thermodynamics, atomic and nuclear physics, electromagnetism, waves and relativity.
- A vast number of professions use some aspect of physics.

Part A will consider the basic mathematical and data skills and applications that will be required for the student experiment, research investigation, data test and practical investigations.

1.2 Orders of magnitude



BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- convert numbers to and from scientific notation
- convert between various units of the same type using SI and some non-SI units.

SCIENTIFIC NOTATION

In scientific research and literature, measurements are often written in **scientific notation** to overcome confusion or ambiguity when displaying numbers with magnitude, for example 2.56×10^{-6}. It is important to understand the numbers in scientific notation, their order of magnitude and how to convert them into other units.

Quantities are written as a number between one and ten and then multiplied by an appropriate power of ten. Note that 'scientific notation', 'standard notation', 'standard form' and 'power of ten notation' all have the same meaning.

SKILLBUILDER 1.2.1

Transforming decimal notation to scientific notation

Scientists use scientific notation to handle very large and very small numbers. For example, instead of writing 0.000 000 035, scientists would write 3.5×10^{-8}.

A number in scientific notation (also called standard form or power of ten notation) is written as:

$a \times 10^n$

where:

a is called the coefficient, and is a real number between 1 and 10, that is $1 \leq a < 10$

n is called the exponent, and is an integer (a positive or negative whole number); n is the power that 10 is raised to.

Note that if n is positive, then the number is larger than one, and if n is negative, then the number is less than 1.

To transform a very large or very small number into scientific notation, perform these steps.

1. Write the original number as a decimal number greater than or equal to 1 but less than 10.
2. Multiply the decimal number by the appropriate power of 10.

The exponent is determined by counting the number of places the decimal point needs to be moved to form the original number again:

- If the decimal point is moved n places to the right, n will be a positive number, for example $510 = 5.1 \times 10^2$.
- If the decimal point is moved n places to the left, n will be a negative number, for example $0.051 = 5.1 \times 10^{-2}$.

TABLE 1.2.1 Converting from scientific notation

Scientific notation	Number (expanded form)
1×10^{-9}	0.000 000 001
1×10^{-6}	0.000 001
1×10^{-3}	0.001
1×10^{-1}	0.1
1	1
1×10^{1}	10
1×10^{3}	1000
1×10^{6}	1 000 000
1×10^{9}	1 000 000 000

You will notice from Table 1.2.1 that when large numbers are written in scientific notation, the 10 has a positive exponential value. Very small numbers smaller than 1 are written with 10 to a negative exponent.

Test the skill

Convert 121 000 to scientific notation.

Examples of some values written in scientific notation are:

6.02×10^{23} particles

$25.25\,\text{mL} = 2.525 \times 10^{-2}\,\text{L}$

$0.00302\,\text{mol} = 3.02 \times 10^{-3}\,\text{mol}$

Values given in scientific notation show the significant numbers and indicate the precision of measurement during experimentation by the instrument. Precision and accuracy are covered in more detail in Module 1.5.

Worked example 1.2.1

CONVERTING TO SCIENTIFIC NOTATION

Write the following values in scientific notation.	
a The number of seconds in 1 day is 86 400.	
Thinking	**Working**
This number is larger than 1, so the exponent will be a positive value. There are 4 placeholders after the first digit, so 4 becomes the exponent.	86 400 has 8 as its first digit. There are 4 placeholders between the 8 and the final zero, so 4 is the exponent.
The coefficient is then 864 with a decimal point placed between the 8 and the 6.	Coefficient is 8.64
Write in scientific notation.	8.64×10^{4} seconds
b The Moon is moving away from Earth at a rate of 0.000 000 001 3 metres per second.	
Thinking	**Working**
This number is less than 1 so the exponent will be a negative number. There are 9 placeholders before the first non-zero digit, so the exponent is –9.	0.000 000 001 3 has 1 as its first non-zero digit. Including the zero in the units column, there are 9 zeros to the left of 1, so –9 is the exponent.
The coefficient is then 13 with a decimal point placed between the 1 and 3.	Coefficient is 1.3
Write in scientific notation.	1.3×10^{-9} metres per second

➤ Try yourself 1.2.1

CONVERTING TO SCIENTIFIC NOTATION

Write the following quantities in scientific notation.

a 4 000 000 m

b 0.000 000 000 000 000 000 1602 C

You should be routinely using scientific notation to express very large and very small numbers. This also involves learning to use your calculator intelligently. Scientific and graphics calculators can be put into a mode whereby all numbers are displayed in scientific notation. It is useful when doing calculations to use this mode rather than frequently attempting to convert to scientific notation by counting digits on the calculator display.

An important reason for using scientific notation is that it removes ambiguity about the precision of some measurements. For example, a measurement recorded as 240 g could be a measurement to the nearest gram; that is, somewhere between 239.5 g and 240.5 g, or it could have been rounded up to the nearest 10 g. By writing this quantity as 2.40×10^{2} g, it makes it clear the accuracy of the value (in this case, 3 significant figures).

Writing numbers using scientific notation

To write a number into long form from scientific notation, follow these rules.

- If the exponent is positive, write the coefficient without the decimal point. Continue to write zeros after the last digit in the coefficient so that the number of placeholders after the first digit is equal to the exponent.
- If the exponent is negative, write a zero in the units placeholder, then a decimal point. Continue to write zeros until the total number of zeros (including the zero in the units placeholder) is equal to the positive value of the exponent. Then write the coefficient without the decimal place.

Worked example 1.2.2

WRITING QUANTITIES FROM SCIENTIFIC NOTATION

Write the following values in long form.

a The mass of the neutron is 1.6749×10^{-27} kg.

b A light year is 9.4607×10^{15} m.

Thinking	Working
a The exponent is negative, which means the number in long form will be less than 1. Write a zero in the units column and then a decimal point. After the decimal point, write another 26 zeros followed by the coefficient without the decimal place.	0.000 000 000 000 000 000 000 000 001 6749 kg
b The exponent is positive, which means the number in long form is greater than 1. Write the coefficient, without the decimal point. There are 4 digits after the 9. So, write 11 more zeros to complete the number. 15 – 4 = 11	9 460 700 000 000 000 m

In both examples the number in long form has been written with three digits grouped together using thin spaces. Sometimes commas are used. This is purely for ease of reading and counting, and is not compulsory.

➤ Try yourself 1.2.2

WRITING QUANTITIES FROM SCIENTIFIC NOTATION

Write the following values in long form.

a The force on an electron in a hydrogen atom is 8.2×10^{-8} N.

b The mass of the Moon is 7.342×10^{22} kg.

Scientific notation is the preferred way of communicating very large and very small measurements and information in physics. Often for convenience and ease of use, quantities in physics problems should first be converted into scientific notation before any calculations can be carried out.

ORDERS OF MAGNITUDE AND PREFIXES

When scientists work with very large or very small numbers, two methods are used to write down a physical measurement: prefixes and scientific notation.

The other form of communicating measured results is to use units that represent the order of magnitude. If 2.56×10^{-6} m was measured, it could be written either in the scientific notation as it is already, or as 256 μm. The symbol μ represents the prefix *micro* (Table 1.2.2), which means 'one millionth of the measured unit'. So, when *micro* is placed in front of metre, it becomes micrometre, meaning 'one millionth of a metre', therefore 256 μm becomes 256 millionths of a metre. Again, these are very small measurements and numbers. An SI **prefix** is a symbol written at the front of a unit to indicate that the measurement is a power of ten higher or lower than the unit itself.

There are 24 SI prefixes in use and most of them denote units that are one thousand (10^3) times larger or smaller than the previous prefix. Table 1.2.2 lists the SI prefixes commonly used in physics. You should become familiar with both scientific notation and prefixes for units of measurement. You should also be able to interchange them.

TABLE 1.2.2 The 24 official SI prefixes

Prefix	Symbol	Multiplier	Description	Decimal	Example
quetta	Q	10^{30}	quintillion	1 000 000 000 000 000 000 000 000 000 000	There is approximately 1400 quintillion litres of water on Earth.
ronna	R	10^{27}	octillion	1 000 000 000 000 000 000 000 000 000	The human body contains approximately 10 octillion atoms.
yotta	Y	10^{24}	septillion	1 000 000 000 000 000 000 000 000	The total power output of the Sun is 383 YW.
zetta	Z	10^{21}	sextillion	1 000 000 000 000 000 000 000	The diameter of the Milky Way galaxy is about 1 Zm.
exa	E	10^{18}	quintillion	1 000 000 000 000 000 000	1 EeV = 0.16 J
peta	P	10^{15}	quadrillion	1 000 000 000 000 000	1 light-year is approximately 10 Pm.
tera	T	10^{12}	trillion	1 000 000 000 000	1 TByte hard drives are now common.
giga	G	10^{9}	billion	1 000 000 000	3.16 Gs = 1 century
mega	M	10^{6}	million	1 000 000	1 MHz is close to the frequencies at which TV stations broadcast.
kilo	k	10^{3}	thousand	1000	1 kg = 1000 grams
hecto	h	10^{2}	hundred	100	1 hPa is a unit used in meteorology to describe atmospheric pressure.
deca	da	10^{1}	ten	10	1 daN is approximately the force exerted by a 1 kg object on the surface of Earth.
–	–	1	unit	1	–
deci	d	10^{-1}	tenth	0.1	1 L = 1 dm^3
centi	c	10^{-2}	hundredth	0.01	1 cg of water takes up 1 mL of space.
milli	m	10^{-3}	thousandth	0.001	There are 1000 mm in 1 m.
micro	µ	10^{-6}	millionth	0.000 001	µg are commonly used as the unit for medicine dosage.
nano	n	10^{-9}	billionth	0.000 000 001	The wavelength of yellow sodium streetlights is 550 nm.
pico	p	10^{-12}	trillionth	0.000 000 000 001	The diameter of the hydrogen atom is about 100 pm.
femto	f	10^{-15}	quadrillionth	0.000 000 000 000 001	Some lasers emit a pulse of light that lasts for 1 fs.
atto	a	10^{-18}	quintillionth	0.000 000 000 000 000 001	Quarks and electrons are believed to be 1 am in size.
zepto	z	10^{-21}	sextillionth	0.000 000 000 000 000 000 001	160 zJ is approximately 1 eV.
yocto	y	10^{-24}	septillionth	0.000 000 000 000 000 000 000 001	The mass of a proton is approximately 1.7 yg.
ronto	r	10^{-27}	octillionth	0.000 000 000 000 000 000 000 000 001	The atomic mass unit (amu) is 1.66×10^{-27} kg
quecto	q	10^{-30}	quintillionth	0.000 000 000 000 000 000 000 000 000 001	The mass of an electron is approximately 1 quintillionth of a kilogram.

SI prefixes are used to avoid writing very small or very large numbers with lots of zeros. The prefix is added directly to the name of a unit, and a prefix symbol attaches directly to the symbol for a unit.

The larger prefixes are written as a capital letter, while the smaller prefixes are written using a lowercase letter. It is important to give a symbol the correct case (upper or lower). There is a big difference between 1 mm (millimetre) and 1 Mm (megametre).

Note that the fundamental unit kilogram has itself a prefix, but all multiples of mass are written with the base unit grams. As an example, one million kilograms is not written as one megakilogram, but as one gigagram (Gg). Do not put spaces between the prefixes and the unit symbols.

Before any measurements with a prefix can be substituted into a formula, they must be converted into SI units without the prefix, i.e. in scientific notation.

SKILLBUILDER 1.2.2

Converting into SI units

Often in science you may need to convert from one unit to another to complete a calculation. Knowing how to change between units is an important skill; however, conversion factors should be used carefully. As some units of measurement are difficult to visualise, knowing the size of different units in relation to each other will aid your understanding and help you avoid errors in your calculations. The most common mistake made with conversion factors is multiplying rather than dividing.

Usually, these conversions are straightforward, such as the conversion between kilometres and meters shown in Worked example 1.2.3 where only the prefix needs to be considered. More detailed conversions will be looked at in module 1.4.

Worked example 1.2.3

CONVERTING INTO SI UNITS

Convert 60 700 grams to kilograms.	
Thinking	**Working**
To convert grams to kilograms, multiply by kg per g.	$= \frac{60\,700}{1} \times \frac{\text{kg}}{\text{g}}$ $= \frac{60\,700}{1} \times \frac{1}{1000}$ $= 60.7\ \text{kg}$

➤ Try yourself 1.2.3

CONVERTING BETWEEN UNITS

Determine how many am (attometres) are in 5.91 ym (yoctometres).

When converting from one unit to another it is essential that you check that the answer makes sense. For instance, if converting from μm to km, you would expect that there are many μm in a km. The inversion of prefix conversions is one of the major sources of mistakes in general physics.

1.2 Review

SUMMARY

- 'Scientific notation', 'standard notation', 'standard form' and 'power of ten notation' all have the same meaning.
- A number in scientific notation is written as $a \times 10^n$, where:
  - a is called the coefficient, and is a real number between 1 and 10, that is, $1 \leq a < 10$
  - n is called the exponent and is an integer (positive or negative).
- A range of scientific symbols is used to represent 10^n.
- The SI prefixes are symbols that go before a unit and indicate multiplication of a power of 10 of the unit.

KEY QUESTIONS

Describe

1 State why physicists need to write numbers in scientific notation instead of long form.

2 Identify the two numbers between which the coefficient of a number expressed in scientific notation has to lie.

3 State what the unit Tg means.

Apply

4 Represent the following values in scientific notation:

a 637 nm, in metres

b 319 s.

5 Represent the following numbers in long form:

a 1.1×10^{-10} m

b 7.031×10^{6} m s^{-2}.

6 Determine the order of magnitude of the following values:

a 6.41×10^{9} m

b 1.201×10^{-3} m^3.

7 Match each number with its scientific notation.

Number	Scientific notation
0.002	2×10^{3}
2000	1.234×10^{-1}
0.1234	2×10^{-3}
123.4	1.234×10^{1}
12.34	1.234×10^{2}

Analyse

8 Convert the following lengths into the unit in brackets, presenting the information in scientific notation:

a 1.56 mm (μm)

b 8.35 nm (cm).

9 A human hair is about 50 μm wide, whereas a virus is 2×10^{-8} m wide. How many times wider than the width of the virus is the width of the human hair?

10 Determine which is the bigger difference in order of magnitude:

a the mass of a human being to the mass of the nucleus of a carbon atom (mass = 1.99×10^{-26} kg)

b the mass of the universe (estimated to be about 5×10^{52} kg) to the mass of a human being

1.3 Mathematical basics for physics

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- understand that the rules of mathematics apply for solving mathematical operations or calculations in physics
- perform basic mathematical operations using percentages and fractions
- rearrange and substitute formulas using algebraic rules
- use the trigonometric ratios to determine side lengths and angles of right-angled triangles
- use the equation of a straight line to determine its gradient and *y*-intercept.

Mathematics is often described as the language of physics. The theories, models, laws and principles used in physics all have their basis in mathematics. Physics extensively uses all aspects of mathematics, from the simplest application of percentage to the addition of three-dimensional magnetic field vectors. To do well in physics you must have knowledge of the following branches of mathematics.

Note that all physics formulas are written using algebraic representation. This means that the **variables** used in any formula are given symbols and their relationship to each other is linked by a set of mathematical operations that include addition, subtraction, multiplication, division, powers and roots.

When conducting mathematical operations or calculations, remember all the rules of mathematics apply, including:

- order of operations
- rules for transposing formulas and working with fractions
- substitutions
- approximations.

PERCENTAGES

Percentages are used when calculating relative amounts of measurements, such as uncertainties and efficiencies.

To calculate a percentage, $P\%$, of an amount, x:

$$x \times \frac{P\%}{100}$$

To express x out of y as a percentage, $P\%$:

$$P\% = \frac{x}{y} \times 100$$

PROBABILITY

In physics, probability is used in thermal, quantum and atomic physics. It is defined as the chance that an event, E, can occur:

$$P(E) = \frac{\text{number of times } E \text{ can occur}}{\text{total number of possible events}}$$

FRACTIONS

Fractions are used extensively throughout physics in such areas as electricity, optics and waves.

When adding or subtracting fractions, the denominators must be equal.

When multiplying fractions, multiply the numerators and write that as a fraction over the denominators multiplied together:

$$\frac{a}{b} \times \frac{c}{d} = \frac{ac}{bd}$$

When dividing fractions, write the divisor (the fraction to be divided) as its reciprocal (i.e. upside-down) and then multiply the fractions together:

$$\frac{a}{b} \div \frac{c}{d} = \frac{a}{b} \times \frac{d}{c} = \frac{ad}{bc}$$

Or, if a whole number, a, is divided by a fraction:

$$a \div \frac{c}{d} = a \times \frac{d}{c} = \frac{ad}{c}$$

EXPONENTS AND LOGARITHMS

Exponent laws

Exponents, (also called indices, or powers) are also used extensively in physics in scientific notation (e.g. $3 \times 10^8\,\mathrm{m\,s^{-1}}$) as well as in many formulas (e.g. $\Delta E = \Delta mc^2$). The following rules for working with exponents may be helpful.

$$a^x \times a^y = a^{x+y}$$

$$a^x \div a^y = \frac{a^x}{a^y} = a^{x-y}$$

$$\left(a^x\right)^y = a^{xy}$$

$$a^0 = 1$$

$$a^1 = a$$

$$a^{-1} = \frac{1}{a}$$

$$a^{-x} = \frac{1}{a^x}$$

$$a^{\frac{1}{2}} = \sqrt{a}$$

$$a^{\frac{1}{x}} = \sqrt[x]{a}$$

Logarithms

Logarithms are a useful mathematical operation that can be used to find the value of exponents. For example, they can be used with decay equations such as $N = N_0\left(\frac{1}{2}\right)^n$.

A detailed analysis of logarithms is beyond the scope of this course. However, logarithms to base 10 (written as just 'log') can be used quite easily to simplify decay equations, instead of using a best-guess method.

The following general rules for working with logs may be helpful.

$$\log xy = \log x + \log y$$

$$\log \frac{x}{y} = \log x - \log y$$

$$\log x^y = y \log x$$

These rules can be used to determine the value of n in the decay equation. Logs are taken of both sides:

$$N = N_0\left(\frac{1}{2}\right)^n$$

$$\log N = \log\left(N_0\left(\frac{1}{2}\right)^n\right)$$

$$\log N = \log N_0 + \log\left(\frac{1}{2}\right)^n$$

$$\log N = \log N_0 + n\log\left(\frac{1}{2}\right)$$

$$n = \frac{\log N - \log N_0}{\log\left(\frac{1}{2}\right)}$$

This can then be solved using the log function on your calculator.

ALGEBRA

Algebra is a powerful tool in solving physics problems. Measurements and data often need to be substituted into a formula in order to obtain an answer. Remember that the data that is to be substituted should always be written without a prefix but in an SI unit, and preferably in scientific notation.

If an unknown variable in a formula needs to be evaluated, then two strategies can be employed:

- The formulas can be rearranged to make the unknown variable the subject of the equation, and then the values substituted in.
- Alternatively, the values can be substituted into the formula and then the formula can be rearranged to make the unknown variable the subject.

Worked example 1.3.1

USING ALGEBRA IN FORMULAS

The kinetic energy (E_k) of a 0.224 kg toy car, m, moving at an unknown speed, v, is 1.61×10^{-3} J.

Kinetic energy is given by the formula:

$$E_k = \frac{1}{2}mv^2$$

Calculate the velocity of the car by first substituting in the known values, and then rearranging the formula.

Thinking	Working
Substitute in the known values.	$E_k = \frac{1}{2}mv^2$ $1.61 \times 10^{-3} = \frac{0.224 \times v^2}{2}$
Rearrange the equation so that v is the subject.	$1.61 \times 10^{-3} \times 2 = 0.224 \times v^2$ $v^2 = \frac{1.61 \times 10^{-3} \times 2}{0.224}$ $v = \sqrt{\frac{(1.61 \times 10^{-3}) \times 2}{0.224}}$
Then solve the equation for v.	$v = \sqrt{\frac{3.22 \times 10^{-3}}{0.224}}$ $= \sqrt{0.014375}$ $= 0.12\ \text{m s}^{-1}$
State the answer using the correct units.	The toy car's velocity is $0.12\ \text{m s}^{-1}$.

➤ Try yourself 1.3.1

USING ALGEBRA IN FORMULAS

The formula relating how much energy per second, P, is released by the Sun is:

$$P = \sigma A T^4$$

where

P is the energy released by the Sun per second in watts

σ is the Stefan–Boltzmann constant $5.67 \times 10^{-8}\,\mathrm{Wm^{-2}K^{-4}}$

A is the surface area of the Sun in $\mathrm{m^2}$

T is the surface temperature of the Sun in kelvin

If the surface area of the Sun is $6.1 \times 10^{18}\,\mathrm{m^2}$, and it produces 3.8×10^{26} watts, determine its surface temperature by first rearranging the formula, then substituting known values.

Quadratic formula

The quadratic formula is sometimes used in more difficult physics problems in which a question can have one, two or no solutions. It is used when the unknown variable is written in an equation with a power of one as well as a power of two. Examples of these questions occur in motion, gravity, electric fields and in electricity.

If $ax^2 + bx + c = 0$, then $x = \dfrac{-b \pm \sqrt{b^2 - 4ac}}{2a}$.

GEOMETRY

Understanding the direction and shape of many abstract ideas in physics requires knowledge of the basics of angles, area, perimeter, volume and trigonometry. These concepts occur throughout every aspect of physics, especially where direction is important.

Pythagoras' theorem

Right-angled triangles are used extensively when vectors are being added or subtracted. Pythagoras' theorem can be used to find unknown side lengths in any right-angled triangle, as shown in Figure 1.3.1.

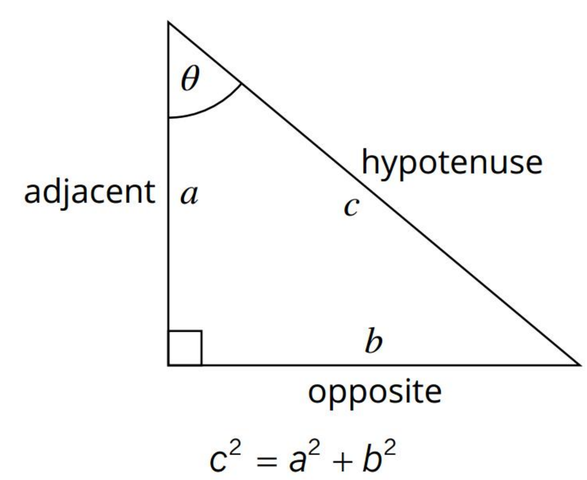


FIGURE 1.3.1 Pythagoras' theorem is used for right-angled triangles.

Trigonometry

The sine, cosine and tangent ratios are also used to determine the sizes and directions of vector quantities in physics. Using the triangle in Figure 1.3.1 the trigonometry ratios can be calculated as follows:

$$\sin\theta = \frac{\text{opposite}}{\text{hypotenuse}} = \frac{b}{c} \qquad \cos\theta = \frac{\text{adjacent}}{\text{hypotenuse}} = \frac{a}{c} \qquad \tan\theta = \frac{\text{opposite}}{\text{adjacent}} = \frac{b}{a}$$

MEASUREMENT

Many concepts in physics require the use and calculation of perimeters, areas, surface areas and volumes. Complex objects are often approximated by circles and spheres.

Circumference, C, of a circle with radius r.

$$C = 2\pi r$$

Area, A, of a circle with radius r.

$$A = \pi r^2$$

Surface area, SA, of a sphere with radius r.

$$SA = 4\pi r^2$$

Volume, V, of a sphere with radius r.

$$V = \frac{4\pi r^3}{3}$$

Volume, V, of a cylinder with height h and base radius r.

$$V = \pi r^2 h$$

STRAIGHT-LINE GRAPHS

A straight line is the simplest relationship between two variables. In graphical analysis of physics phenomena, a straight line is useful, as the y-intercept and gradient can be calculated. Figure 1.3.2 shows a typical straight-line relationship.

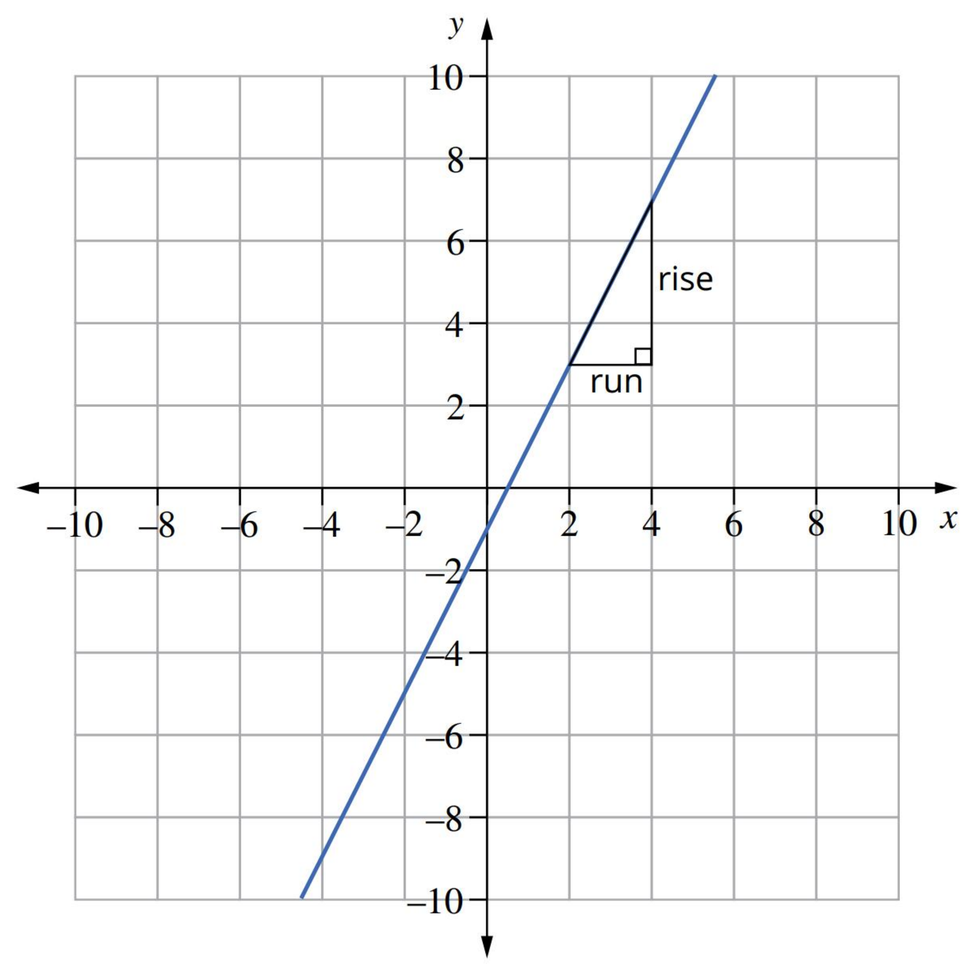


FIGURE 1.3.2 A graph representing a simple relationship between two variables

The gradient of any straight line is calculated using:

$$\text{gradient, } m = \frac{\text{rise}}{\text{run}} = \frac{\Delta y}{\Delta x}$$

The y-intercept, c, is read off the y-axis.

The equation of any straight line is determined by the gradient and y-intercept:

$$y = mx + c$$

In the example in Figure 1.3.2, the equation of the straight line is $y = 2x - 1$ with a gradient of 2 and y-intercept of -1.

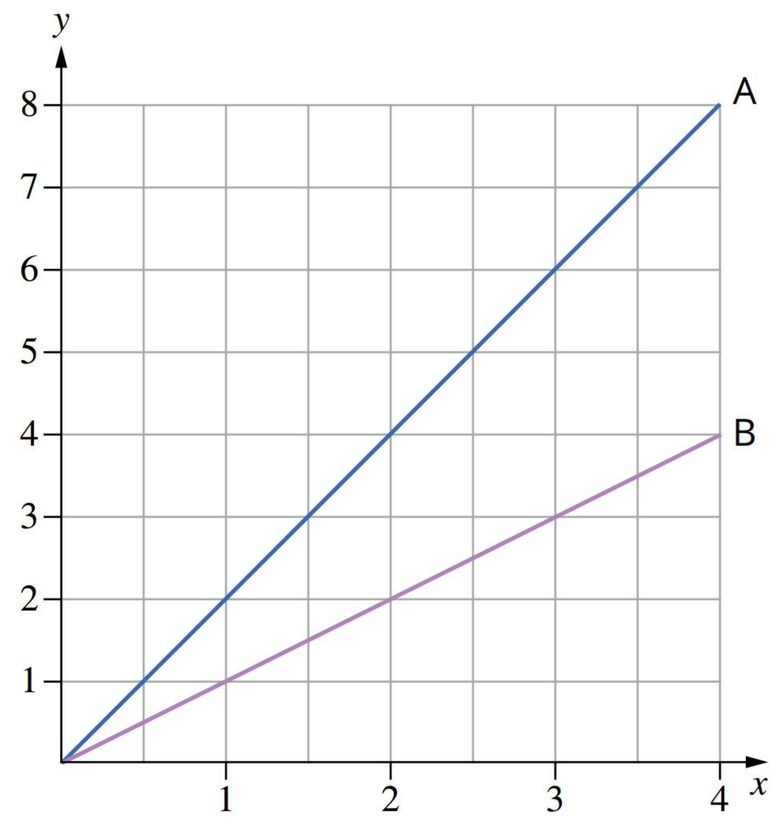
SKILLBUILDER 1.3.1

Interpreting the slope of a straight-line graph

Scientists often represent a relationship between two variables as a graph. For directly proportional relationships, the variables are related to each other by a straight line, where the slope (or gradient) of the line represents the constant of proportionality between the two variables.

The slope or gradient of the line is defined as the ratio of change between two points in the vertical axis (Δy), divided by the change between two points in the horizontal axis (Δx). In other words, it measures the rate at which one variable (the dependent variable) changes with respect to the other (the independent variable).

The graph shown has two straight lines with different slopes. The steeper slope (blue line, A) indicates that the rate of change is higher. This means the change is happening more quickly. On the other hand, the flatter slope (lilac line) indicates that the rate of change is lower. This means the change is happening more slowly.



More information about interpreting the relationship between two variables is in Module 1.6.

Worked example 1.3.2

INTERPRETING THE SLOPE OF A LINEAR GRAPH

On a graph with two sloped lines, identify what the steeper sloped line indicates.

A a faster rate of change

B a slower rate of change

C the same rate of change

D a much slower rate of change

Thinking	Working
The slope or gradient of the line is defined as the ratio of change between two points in the vertical axis (Δy), divided by the change between two points in the horizontal axis (Δx).	**A** is correct. The steepness of the slope indicates the rate of change. A line with a steeper slope indicates a faster rate of change.

➤ Try yourself 1.3.2

INTERPRETING THE SLOPE OF A LINEAR GRAPH

Identify which of the following options indicates the rate of change of a straight line on a graph.

A area under the graph

B *y*-intercept

C *x*-intercept

D gradient

1.3 Review

SUMMARY

- When conducting mathematical operations or calculations, remember all the rules of mathematics apply, including:
  - order of operations
  - rules for transposing formulas and working with fractions
  - substitutions
  - approximations.
- Percentages and fractions are basic mathematical skills that are applicable in all fields of physics.
- Performing substitution and rearranging of physics formulas is vital to solving numerical calculations.
- The trigonometric ratios of sine, cosine and tangent are used to determine the directions of many physical quantities.
- Complex shapes can be approximated using circles, spheres and cylinders, and then calculating their area, surface area and volume using the appropriate formula.
- The analysis of a straight line is very important in physics as the gradient and *y*-intercept often contain useful information about physical relationships.

KEY QUESTIONS

Describe

1 State the formula for calculating the gradient of a straight line.

2 Write the three trigonometric ratios in terms of the sides of a right-angled triangle.

Apply

3 Determine the gradient (m) and y-intercept of the following straight lines:

a $y = x - 7$

b $2y = 16 - 4x$

c $4.5y + 2.1x - 7 = 0$.

4 Rearrange the following formulas so that the variable in brackets is the subject of the equation:

a $F = ma$ (a)

b $E_k = hf - W$ (f)

c $F = \dfrac{GMm}{r^2}$ (r).

Analyse

5 A student recorded the following temperatures of water.

Time (min)	Temperature (°C)
0	22
2	34
4	43
5	50
8	64
10	78

a Calculate the average temperature change per minute during the experiment.

b Determine whether the increase was constant throughout the experiment.

6 WASP-17b is an exoplanet discovered in 2009 that has a radius twice that of Jupiter. Determine how many times the volume of Jupiter this is. The relationship between the radius, r, and volume, V, of a sphere is given by the formula $V = \dfrac{4\pi r^3}{3}$.

7 Solve the following problems.

a $\dfrac{1}{2} + \dfrac{1}{8}$

b $10 \div \dfrac{4}{5}$

c 15% of 76.2 kg.

8 Simplify each of the following:

a $\dfrac{t^3 \times t}{\sqrt{t}}$

b $c\left(\dfrac{c^2}{c}\right)^3$.

9 Substitute the following values into the formula below to obtain a value and units for γ:

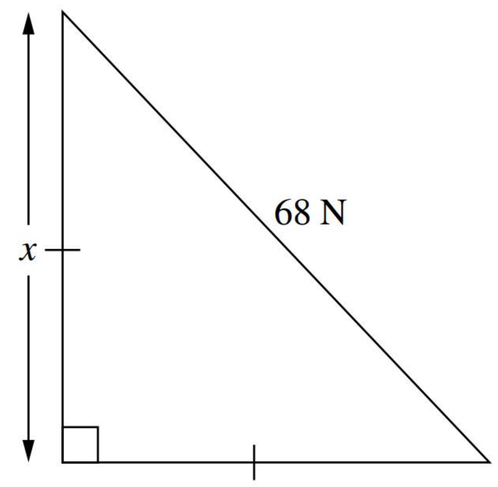
$c = 3.00 \times 10^8\,\text{m s}^{-1}$

$v = 2.99 \times 10^8\,\text{m s}^{-1}$

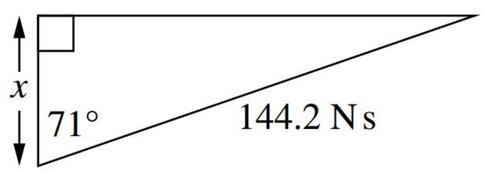
$$\gamma = \frac{1}{\sqrt{1 - \dfrac{v^2}{c^2}}}$$

10 Determine the value of x in the following triangles:

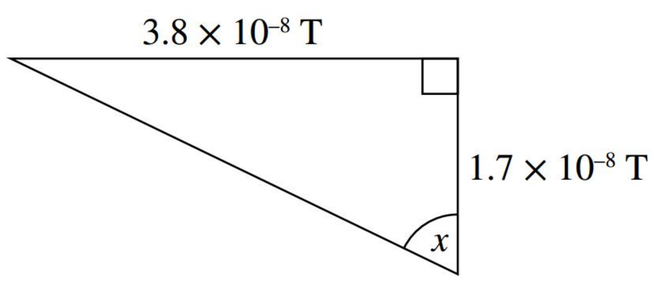
a



b



c

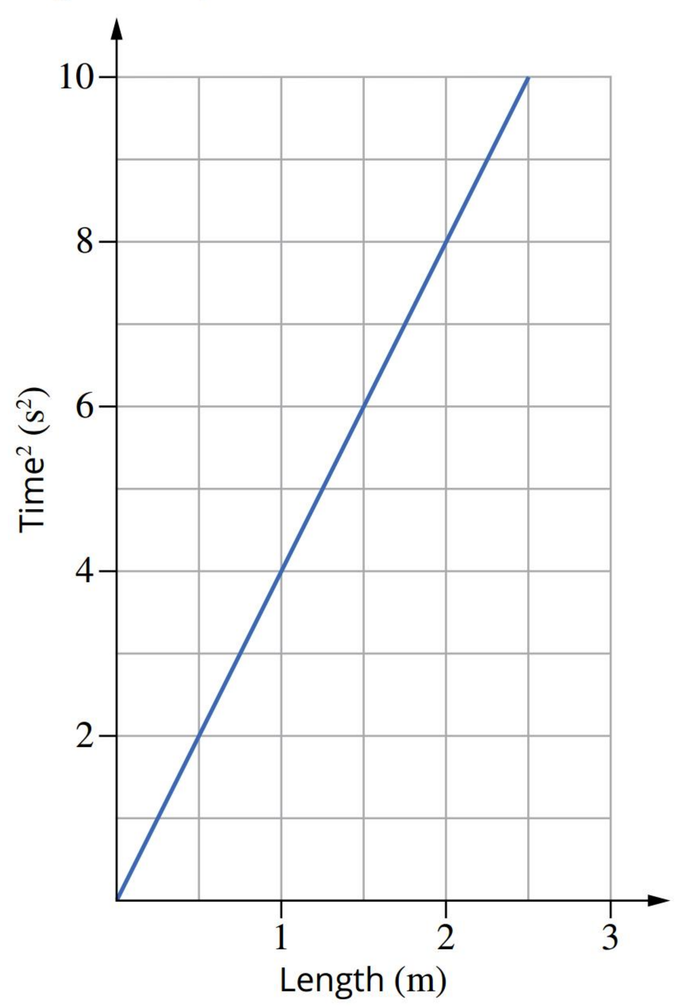


11 Solve the following equation for a positive value of x.

$$\frac{kq^2}{x^2} = \frac{4kq^2}{(1-x)^2}$$

where k and q are constants.

12 The graph below shows how the time for one complete swing of a pendulum, squared, changes with the length of a pendulum.



a Determine the gradient and y-intercept of the line.

b Identify the units of the gradient and y-intercept.

c If the gradient of the line is theoretically equal to $\frac{4\pi^2}{g}$, determine the value, and units, of g.

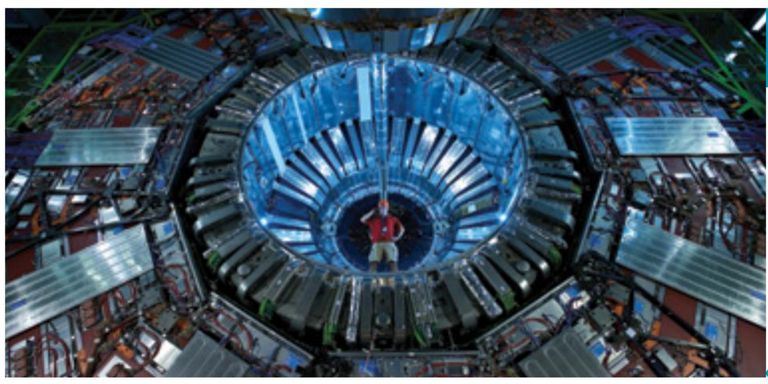
13 Rearrange $N = N_0\left(\frac{1}{2}\right)^n$ to make n the subject.

14 Solve for n in the following equations:

a $0.25 = 2\left(\frac{1}{2}\right)^n$

b $20 = 450\left(\frac{1}{2}\right)^n$

1.4 Units



BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- appreciate that physics uses the International System (SI) of units
- recall fundamental units, their symbols and definitions
- convert between various units of the same type using SI and some non-SI units.

Science uses a specific system of units to describe measurements that are made. In physics, measurements are made using the **International System (SI)** of units. Most countries around the world use and understand these units as they are internationally accepted in science, commerce, sport and everyday life.

MEASUREMENT AND UNITS

Every science needs a system of units to describe the measurements that are made. In physics, measurements are made using the International System (SI) of units. Make sure the units you measure or observe are accurate and remember to use SI units when recording your evidence. Table 1.4.1 presents common quantities and SI units used in physics.

TABLE 1.4.1 The seven fundamental SI units used in physics, along with their symbols

Quantity	SI unit	Symbol for SI unit
length	metre	m
mass	kilogram	kg
time	second	s
electric current	ampere	A
temperature	kelvin	K
amount of substance	mole	mol
luminous intensity	candela	cd

Correct use of unit symbols

The correct use of unit symbols removes ambiguity, as symbols are recognised internationally. Some important points to keep in mind when writing units and recording measurements and numbers are given in Table 1.4.2.

Uppercase letters are only used for the *symbols* of the units that are named after people. For example, the unit of energy is joule and the symbol is J. The joule was named after James Joule who was famous for studies into energy conversions. The exception to this rule is 'L' for litre. Uppercase 'L' is used because a lowercase 'l' looks like the numeral '1'.

The product of several units is shown by separating the symbol for each unit with a space. The division or ratio of two or more units can be shown in fraction form, using a slash, or using negative exponents. Prefixes should not be separated by a space.

TABLE 1.4.2 Examples of correct and incorrect use of symbols for derived units

Rule	✓	✗
Numbers and symbols should not be mixed.	thirty grams 30 g	thirty g 30 grams
Do not put spaces between prefixes and unit symbols.	kg mL kPa	k g m L k Pa
Write the correct case for symbols (upper- or lower-case).	1 mm 84 kg 5.2 mL	1 Mm 84 KG 5.2 m L
SI units should not be followed by a full stop unless they are at the end of a sentence. The symbols for units are not abbreviations.	12.1 mm	12.1 mm.
Only use upper-case letters for unit symbols named after people. The exception is 'L' for litre, to avoid confusion because 'l' looks like the numeral '1'.	J	j
Units can take the plural form by adding an 's' when used with numbers greater than one. Never do this with the unit symbols.	two kilojoules	2 kJs
The product of two or more units is shown by separating the symbol for each unit with a space.	0.1 mol dm^{-3}	0.1 moldm^{-3}
The division or ratio of two or more units can be shown in fraction form, using a slash, or using negative exponents. A space is always used between different units. For example, closing up metres and seconds as ms suggests that m is a prefix (milli) rather than a unit (metres).	9.8 m/s 9.8 m s^{-1}	9.8 ms^{-1} 9.8 m/s^{-1}

When units are displayed with a negative exponent, such as m s^{-1}, the negative value of the exponent signifies the division of the units, in other words, per unit. In this case, m s^{-1} is the same as m/s, or metres per second.

DERIVED UNITS

Every other unit that is used in physics is a mathematical combination (such as division, multiplication, squaring) of one or more of the seven fundamental units, and are called derived units. Table 1.4.3 lists some of the most common units encountered in high school physics.

TABLE 1.4.3 Some of the most common derived units in high school physics

Quantity and symbol	SI unit	Symbol for SI unit	Notes
area, *A*	square metre	m^2	
volume, *V*	cubic metre	m^3	
amount of liquid, *V*	litre	L or l	$1\,L = 1000\,cm^3 = 0.001\,m^3$
density, *ñ*	kilograms per cubic metre	$kg\,m^{-3}$	
velocity, *v*	metres per second	$m\,s^{-1}$	
acceleration, *a*	metres per second squared	$m\,s^{-2}$	
current, *I*	ampere	A	
momentum, *p*	kilogram metres per second	$kg\,m\,s^{-1}$	$1\,kg\,m\,s^{-1} = 1\,N\,s$
force, *F*	newton	N	$1\,N = 1\,kg\,m\,s^{-2}$
energy, *E*	joule	J	$1\,J = 1\,N\,m$
power, *P*	watt	W	$1\,W = 1\,J\,s^{-1}$
charge, *q*	coulomb	C	$1\,C = 1\,A\,s$
frequency, *f*	hertz	Hz	$1\,Hz = 1\,s^{-1}$
pressure, *P*	pascal	Pa	$1\,Pa = 1\,N\,m^{-2}$
voltage, *V*	volt	V	$1\,V = 1\,J\,C^{-1}$
resistance, *R*	ohm	Ω	$1\,\Omega = 1\,V\,A^{-1}$
magnetic flux density, *B*	tesla	T	$1\,T = 1\,N\,A^{-1}\,m^{-1}$
magnetic flux, ϕ	weber	Wb	$1\,Wb = 1\,T\,m^2$
activity, *A*	becquerel	Bq	$1\,Bq = 1$ decay s^{-1}

A derived unit is a unit that is a mathematical combination of one or more of the seven fundamental units.

NON-SI UNITS USED IN PHYSICS

Two non-SI units are used extensively in physics, the kWh and the eV, and they are both units of energy.

The kilowatt-hour, kWh, is used to describe the amount of energy used or supplied to homes by power stations. Note that this unit is not kilowatts *per* hour but kilowatts times hour.

$$1\ kWh = 3.60 \times 10^6 J$$

The electron volt, eV, is used to describe the energies of subatomic particles.

$$1\,eV = 1.602 \times 10^{-19} J$$

UNIT CONVERSIONS

When derived units are used, conversion factors are required (such as 1 minute = 60 seconds). For example, values of energy can be converted between electron volts (eV) and joules (J) using $1\,\text{eV} = 1.602 \times 10^{-19}\,\text{J}$.

Care should be taken when unit conversions involve non-SI units and rates. One example is the conversion between kilometres per hour and meters per second. In this case the kilometres would need to be converted to meters and the hours would need to be converted to seconds:

$100\,\text{km} = 1\,000\,000\,\text{m}$

1 hour = 60 minutes = 3600 seconds

So, $100\,\text{km}\,\text{h}^{-1} = \frac{100\,\text{km}}{1\,\text{h}} = \frac{1000\,000\,\text{m}}{3600\,\text{s}} = 27.8\,\text{m}\,\text{s}^{-1}$

A similar example is the conversion between units for volume and capacity in Worked example 1.4.1.

Worked example 1.4.1

UNIT CONVERSIONS

Calculate how many litres are in one cubic kilometre.	
Thinking	**Working**
Write each unit in terms of m^3. Remember that a km^3 is a cube that has sides of 1000 m by 1000 m by 1000 m.	$1\,\text{L} = 0.001\,\text{m}^3$ and $1\,\text{km}^3 = 1000\,\text{m} \times 1000\,\text{m} \times 1000\,\text{m} = 10^9\,\text{m}^3$
Take the inverse of each equation to find the equivalent volume in m^3.	$1\,\text{m}^3 = \frac{1}{10^9} = 10^{-9}\,\text{km}^3$ and $1\,\text{m}^3 = \frac{1}{0.001} = 10^3\,\text{L}$
Now equate them since they are both equal to $1\,\text{m}^3$.	$10^{-9}\,\text{km}^3 = 10^3\,\text{L}$ $\therefore \frac{10^3\,\text{L}}{10^{-9}\,\text{km}^3} = 10^{12}\,\text{L}\,\text{km}^{-3}$
State the answer.	There are 10^{12} or one trillion litres in 1 cubic kilometre.

➤ Try yourself 1.4.1

UNIT CONVERSIONS

If a person weighs 6.0×10^1 kg and the mass of a single carbon atom is 1.99×10^{-23} g, calculate how many carbon atoms would be needed to equal the mass of the person.

1.4 Review

SUMMARY

- Physics uses the International System (SI) of units.
- There are seven fundamental units: metre, second, kilogram, kelvin, mole, ampere and candela.
- Units with a prefix need to be converted into scientific notation before they can be used in a physics formula.
- When converting units, it is very useful to write the conversions as fractions and then cross-cancel out to ensure that the conversion is done correctly.
- When units are displayed with a negative exponent, the negative value of the exponent signifies the division of the units. For example, g mL^{-1} is the same as g/mL or grams per millilitre.
- When writing and recording measurements, remember:
  - numbers and symbols should not be mixed
  - do not put spaces between prefixes and unit symbols
  - write the correct case for symbols (upper or lower).

KEY QUESTIONS

Describe

1 State the standard unit of measurement, and the symbol, for the following quantities:

a time
b temperature
c length
d mass.

2 List the following units from largest to smallest: centi, milli, deci, mega, kilo, nano, micro.

Apply

3 Explain why it is important that general society, not just the scientific community, needs a systematic and consistent set of units for measurement.

4 Explain the difference between fundamental units and derived units.

Analyse

5 Convert 30.00 mL into L.

6 Identify any errors in the recordings below and correct them:

a 23 mL/g h^{-1}
b 79 Kl s^{-1}
c four litres
d 1.56 grams.

7 Determine how many metres there are in the 656 nanometres wavelength of red light emitted from hydrogen.

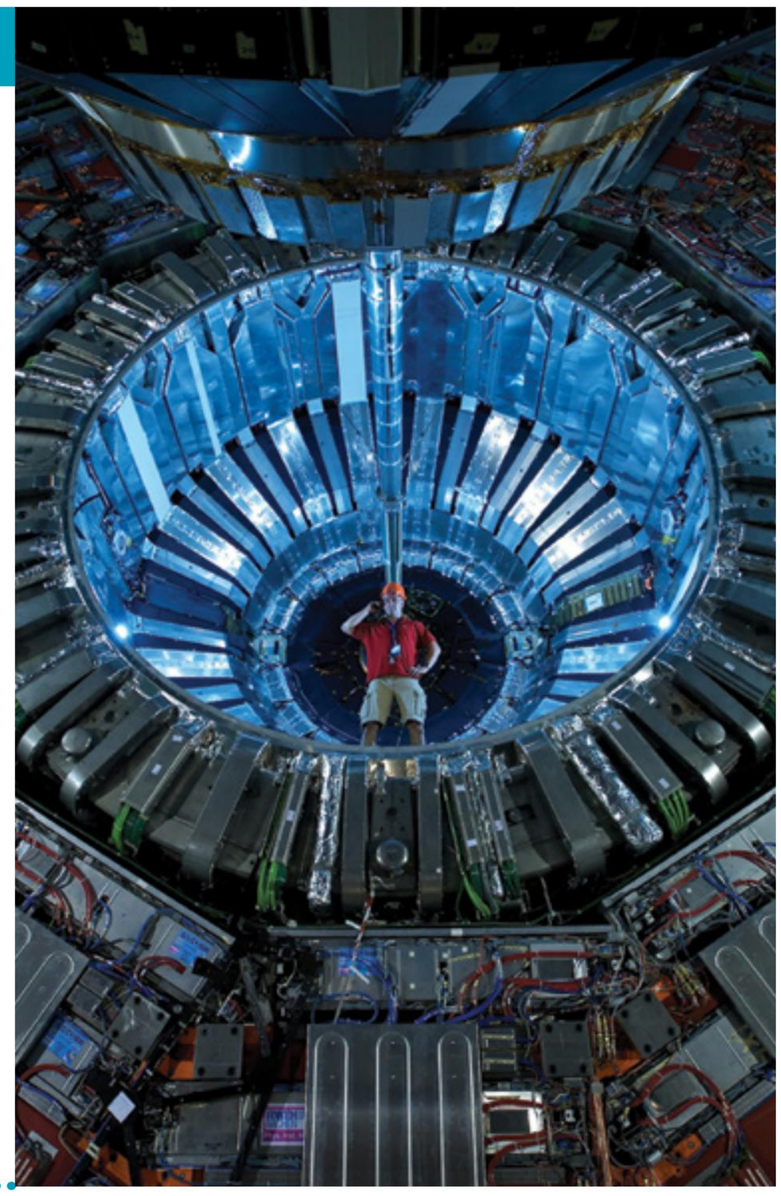
8 Show that the unit ohm can be written in fundamental units as:

$$1\,\Omega = 1\left(\frac{kg\,m^2}{A^2\,s^3}\right)$$

1.5 Uncertainty and error

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- explain the difference between accuracy and precision
- explain the difference between uncertainty and error
- calculate uncertainty and error values for measurements
- write measurements with uncertainty and error values
- write measurements and calculations to the correct number of significant figures
- perform calculations that contain uncertainty or error values
- understand that all measurements made in physics experiments are subject to a level of uncertainty
- differentiate between accuracy and precision, and know how to express these quantitatively using significant figures
- perform calculations using significant figures
- explain the difference between mistakes, systematic uncertainties and random uncertainties
- determine the absolute uncertainty of a value based on the precision of the instrument
- convert between absolute and percentage uncertainties
- calculate a value along with the associated uncertainty.



All measurements are limited by the instrument used and the observer. Accuracy of the measurements and results are therefore affected. Instruments have a prescribed level of precision and cannot measure within the smallest increment of the device. In addition, a scientist's technique and experience with the instrument influences the precision with which the reading can be made.

However, in science it is impossible to measure the true value, as there will always be some degree of **uncertainty**. This results in **error** and uncertainty in the values measured or observed. Therefore, science can be thought of as developing evidence-based results that have some limitations. Measurements with uncertainty and errors are normal in science and so results are always presented with a **range** (e.g. ±0.5) indicating possible precision, or processed through statistical calculations.

ACCURACY AND PRECISION

In science and statistics, the terms *accuracy* and *precision* have very specific and different meanings.

- **Accuracy** is the ability to obtain the correct measurement. To obtain accurate results, you must minimise **systematic errors**.
- **Precision** is the ability to consistently obtain the same measurement. To obtain precise results, you must minimise **random errors**.

The percentage error (or measurement error written as a percentage) in the measurement is the difference between the measurement and the accepted value, written as a percentage:

$$\text{percentage error (\%)} = \left|\frac{\text{measured value} - \text{accepted value}}{\text{accepted valued}}\right| \times 100\%$$

The accuracy of a measurement is how close it is to an accepted value.

The precision of a measurement is how many digits can be written down to describe the measurement.

As an example, the speed of light is $299\,792\,453\,\mathrm{m\,s^{-1}}$.

An accurate measurement for the speed of light is $300\,000\,000\,\mathrm{m\,s^{-1}}$, which has only a 0.07% percentage error:

$$\left|\frac{300\,000\,000 - 299\,792\,453}{299\,792\,453}\right| \times 100\% = 0.07\%$$

An inaccurate measurement for the speed of light is $780\,000\,000\,\mathrm{m\,s^{-1}}$, which has a 160% percentage error:

$$\left|\frac{780\,000\,000 - 299\,792\,453}{299\,792\,453}\right| \times 100\% = 160\%$$

Devices that use smaller and smaller units to measure in are also said to be precise. Common examples are Vernier callipers and micrometers.

To understand more clearly the difference between accuracy and precision, think about firing arrows at an archery target (Figure 1.5.1). Accuracy is being able to hit the bullseye, whereas precision is being able to hit the same spot every time you shoot.

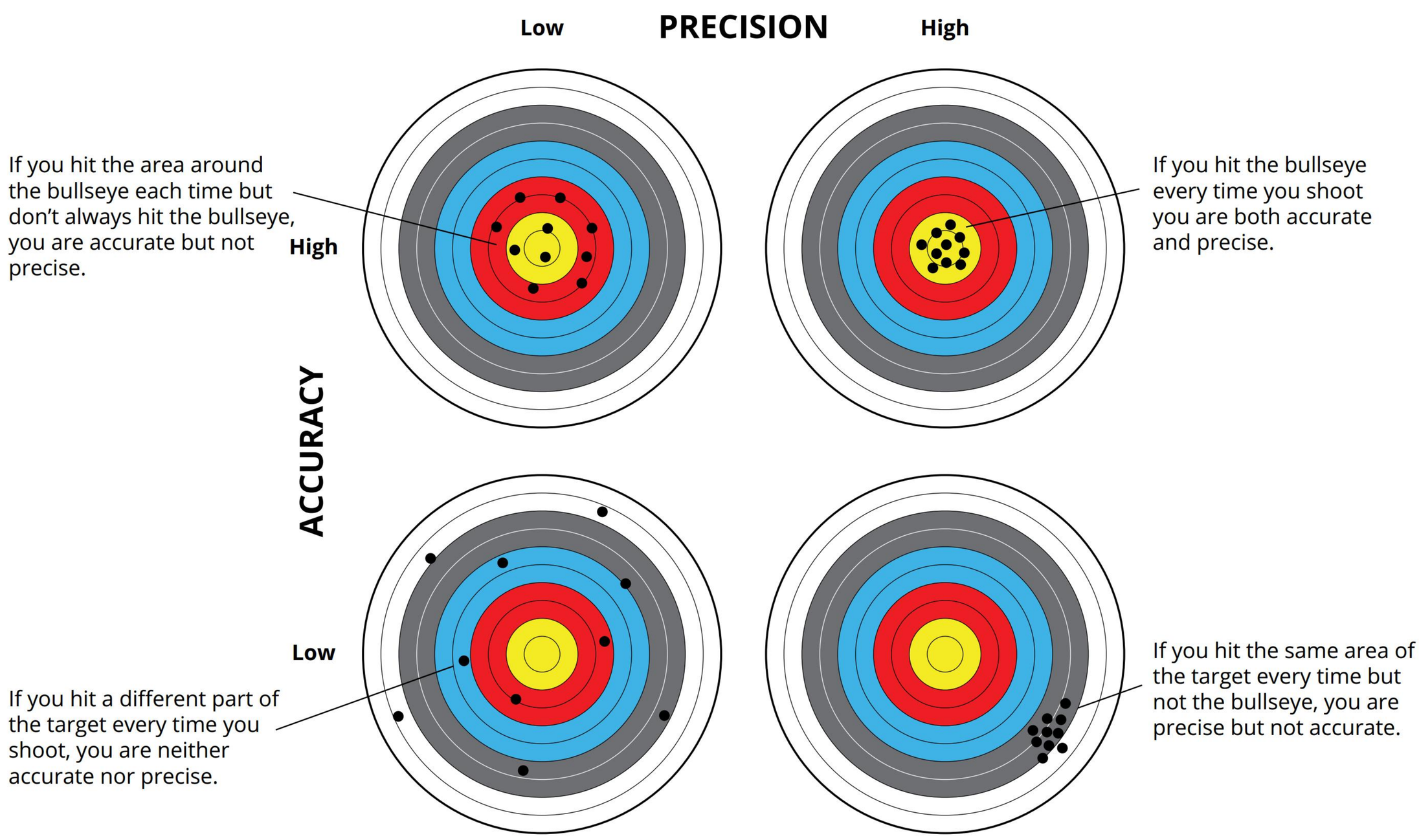


FIGURE 1.5.1 Hitting an archery target with arrows illustrates the difference between accuracy and precision. In summary, measurements should be both precise and as accurate as you can make them.

Recording numerical data

When using instruments to measure data, the number of significant figures (or digits) and decimal places you use is determined by how precise your measurements are.

The overall precision of the measurement depends on the scale, accuracy and precision of the instrument and technique you are using (Figure 1.5.2). For example, a beaker may be used to measure volumes approximately and has limited accuracy of, for example, ±5%; however, a graduated pipette is much more accurate, with accuracies of ±0.1% or ±0.2%. Your pipette may be accurate but if your technique using the pipette is variable, the overall accuracy and precision will be limited.

When you record **raw data** and report processed data, you must use the number of significant figures available from your equipment or **observation**. (This is discussed in more detail in Module 1.10.) Using either a greater or smaller number of significant figures can be misleading. For example, Table 1.5.1 shows measurements of five mass samples taken using an electronic balance accurate to 2 decimal places. The data was entered into a spreadsheet to calculate the mean (or average), which was displayed with 4 decimal places. You would record the mean as 20.83 g, not 20.8260 g, because 2 decimal places is the precision limit of the instrument. Recording 20.8260 g would be an example of false precision.

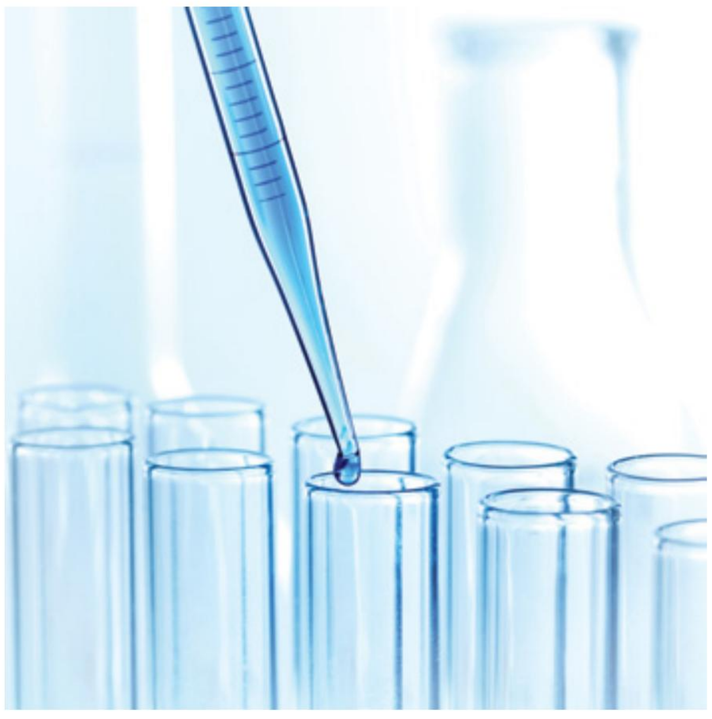


FIGURE 1.5.2 A 5 mL graduated pipette can measure volumes to an accuracy of one-tenth of a millilitre, or 5 mL ± 0.1 mL. The pipette has major divisions of 1 mL and minor divisions of 0.1 mL. You can estimate to 0.05 mL and record volumes to 2 decimal places, for example, 3.80 mL or 4.55 mL.

TABLE 1.5.1 An example of false precision in a data calculation

Sample	1	2	3	4	5	Mean
Mass (g)	20.13	20.62	21.22	20.99	21.17	20.8260

UNCERTAINTY AND ERROR

Uncertainty is a range of measurement from the experiment, within which the true value is expected to lie. Due to sources of error and uncertainty, an estimation is made to suggest where the true value should be found among the measurements. Uncertainty is one indicator of a limitation. Expressed as a ± value, uncertainty can be derived either from the known precision of the equipment or alternatively from calculations involving the range of trials (see 'measurement uncertainty' and 'uncertainty of the mean').

Error

Error is the difference between a measurement and the true value. This is not an indication of human error or mistakes. It is due to an inability to achieve the true value. Error cannot be eliminated, and therefore it is important to understand and record the error and report it. Two types of errors can occur—systematic error and random error (Table 1.5.2).

TABLE 1.5.2 Systematic and random errors

Error	Definition	Cause	Example
systematic	An error in measurements caused by the design of a system (e.g. methodology) or instrument (uncalibrated), which results in the measurements shifting in a systemic direction. The mean may be displaced or varied in a predictable way affecting the accuracy of the measurement. It is quantified by calculating percentage error.	• instrument calibration (Figure 1.5.4) • choice of instrument • precision of instrument (increments) • precision of instrument (sample rate—per second) • sampling (the choice of population or representatives) • heat loss to the surroundings	The balance used for weighing out samples reads 0.05 g too high for all your masses (because it was improperly tared (set to zero) at the start of the experiment). A thermometer is not calibrated to the correct temperature. All temperatures will be slightly off by the same amount. If this amount can be determined, the data can be corrected.
random	An error that affects the measurement in an unpredictable way, resulting in an even variation (fluctuation) in measurements above and below the expected true value. This affects the precision of the measurement. It is quantified by calculating percentage uncertainty.	• estimation (measuring between increments) • sampling (frequency, spread, increments) • parallax (Figure 1.5.3) • instrument sensitivity • noise	Using a stopwatch to measure time involves the random reaction time and judgments of the measurer. Measuring an electric field using a sensor which also picks up random background noise from electronic devices in the room.

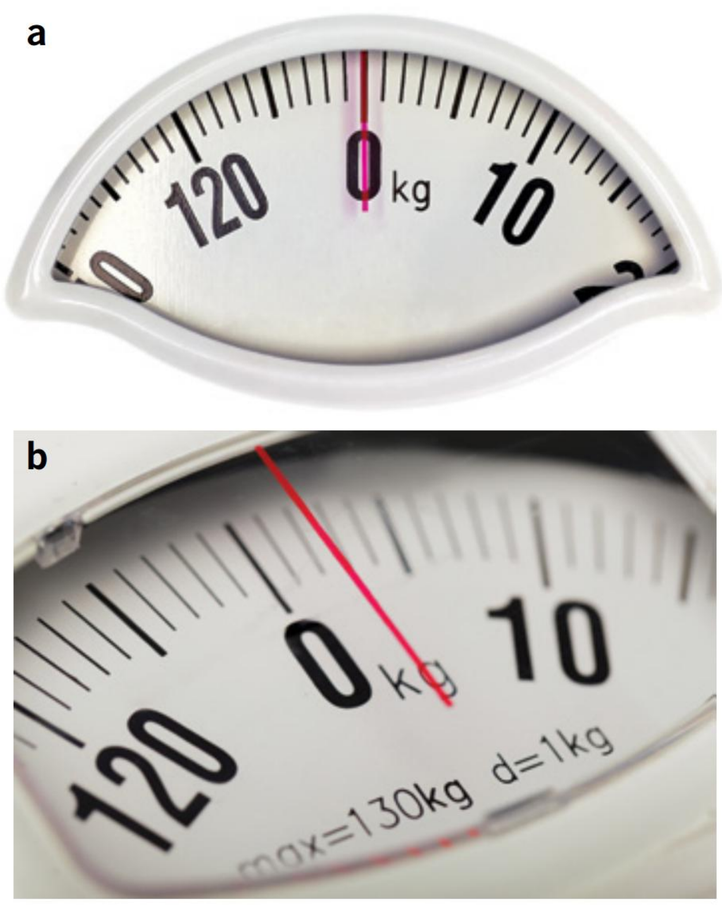


FIGURE 1.5.3 (a) The correct reading of 0 kg is obtained when the scale is viewed from directly in front. (b) An incorrect reading of 2 kg is obtained because of parallax error when reading an analog scale at an angle.

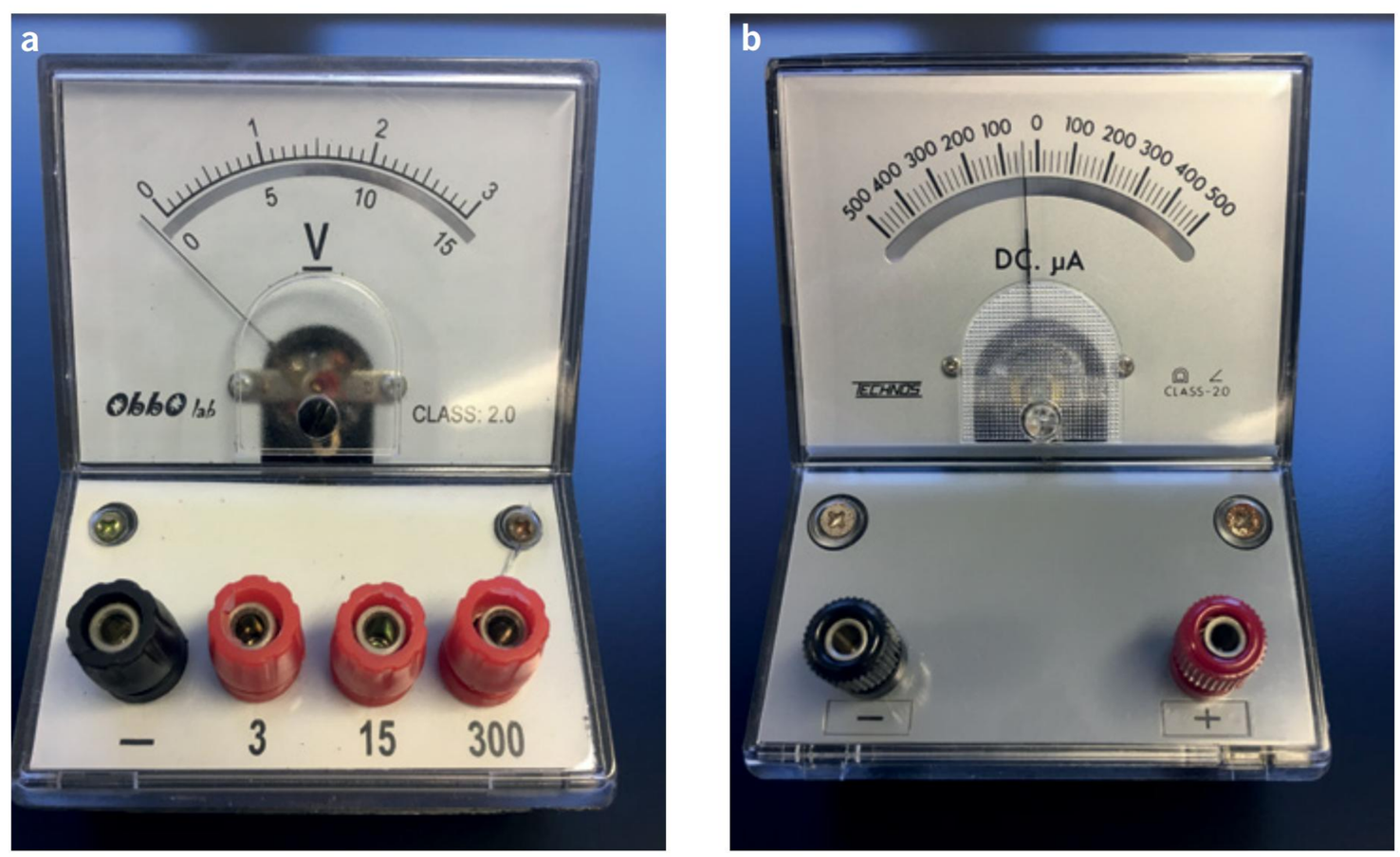


FIGURE 1.5.4 Three examples of zero error on analog instruments: (a) voltmeter (b) ammeter and (c) a digital instrument (an electronic balance)

Determining uncertainty in a single measurement

When using an instrument to measure a property of an object, there will always be a limit as to how precise the reading can be. In a physics experiment, analog and digital instruments are both used and measurements are determined slightly differently depending on which device is used.

The precision that can be read off a single instrument is called the limit of reading. This is the smallest visible graduation on an analog instrument, or, if a digital instrument is used, then the limit of reading is usually the smallest decimal place given on the screen.

For most analog instruments, the **absolute measurement uncertainty**, Δx, in a measurement of x is exactly half of the limit of reading for each part of the measured object that has to be lined up. This means that the actual measurement could be anywhere from half of the smallest graduation too big to half of the smallest graduation too small.

Some analog instruments have a zero mark and a reading mark, such as the ruler shown in Figure 1.5.5a. The object to be measured has to be lined up at both ends, therefore doubling the absolute uncertainty. For rulers and protractors, the absolute uncertainty is equal to the limit of reading, not half of it.

For a digital instrument, Δx is typically the limit of reading, or the smallest decimal place given on the screen. An example of this is a high-precision electronic balance, as shown in Figure 1.5.5b.

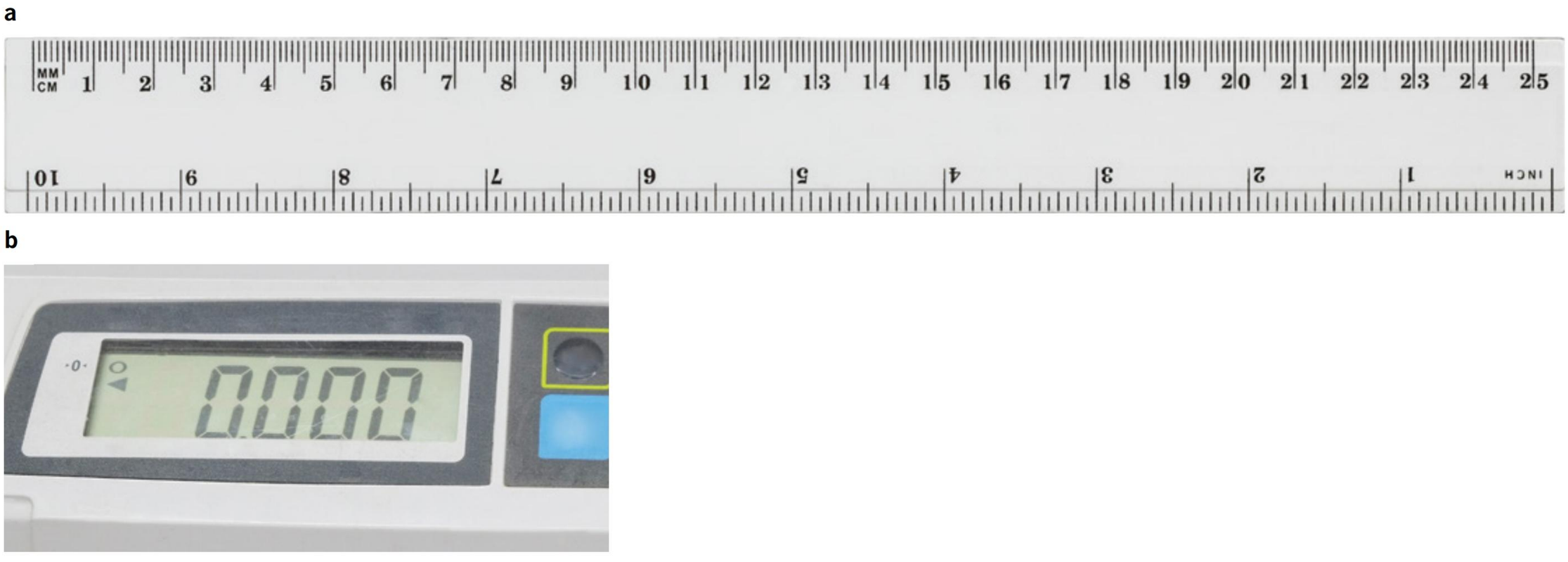


FIGURE 1.5.5 (a) The ruler has a limit of reading of 1 mm and (b) the electronic balance has a limit of reading of 0.001 g.

For analog instruments that have one scale to line up (such as a measuring cylinder, thermometer or voltmeter), the absolute uncertainty, Δx, in a measurement of x is exactly half of the limit of reading for each part of the measured object that has to be lined up.

For analog instruments that have two scales to line up (such as rulers and protractors) the absolute uncertainty, Δx, is equal to the smallest graduation scale, or limit of reading.

For digital instruments the absolute uncertainty, Δx, is equal to the smallest decimal place displayed.

Table 1.5.3 summarises the limit of reading and absolute uncertainty of common analog instruments used in a high school physics laboratory.

TABLE 1.5.3 A summary of common instruments and their uncertainties used in a physics laboratory

Instrument	Type of instrument	Limit of reading	Absolute uncertainty	Example	Notes
mm ruler	analog	1 mm	± 1.0 mm	123.8 ± 1.0 mm	Half of the limit of reading is 0.50 mm, but the object to be measured has to be lined up at both ends, so the uncertainty is double this, or ±1.0 mm.
cm ruler	analog	1 cm	± 1.0 cm	31.4 ± 1.0 cm	As for a mm ruler.
Vernier callipers	analog	0.05 mm	0.05 mm	19.44 ± 0.05 mm	Vernier calipers and micrometers use screws to determine the measurement (shown in Figure 1.5.6).
micrometer	analog	0.01 mm	± 0.01 mm	7.13 ± 0.01 mm	
thermometer	analog	1.0°C	± 0.5°C	24.4 ± 0.5°C	Only the top part of the liquid in the thermometer has an uncertainty, so the uncertainty is exactly half of the limit of reading.
measuring cylinder	analog	1.0 mL	± 0.5 mL	15.7 ± 0.5 mL	The limit of reading and absolute uncertainty depend on the size of the measuring cylinder.
protractor	analog	1.0°	± 1.0°	30.1 ± 1.0°	The two lines that make up the angle have to be lined up, so the uncertainty is twice half of the limit of reading, similar to that in mm and cm rulers.
stopwatch	digital	0.01 s	from ± 0.1 to ± 0.4 s	9.6 ± 0.2 s	The limit of reading is not the absolute uncertainty for a stopwatch because the user's reaction time (usually between 0.1 and 0.4 s) needs to be taken into consideration.
electronic balance	digital	typically 0.01 g	± 0.01 g	7.03 ± 0.01 g	The absolute uncertainty is the smallest possible decimal place displayed.

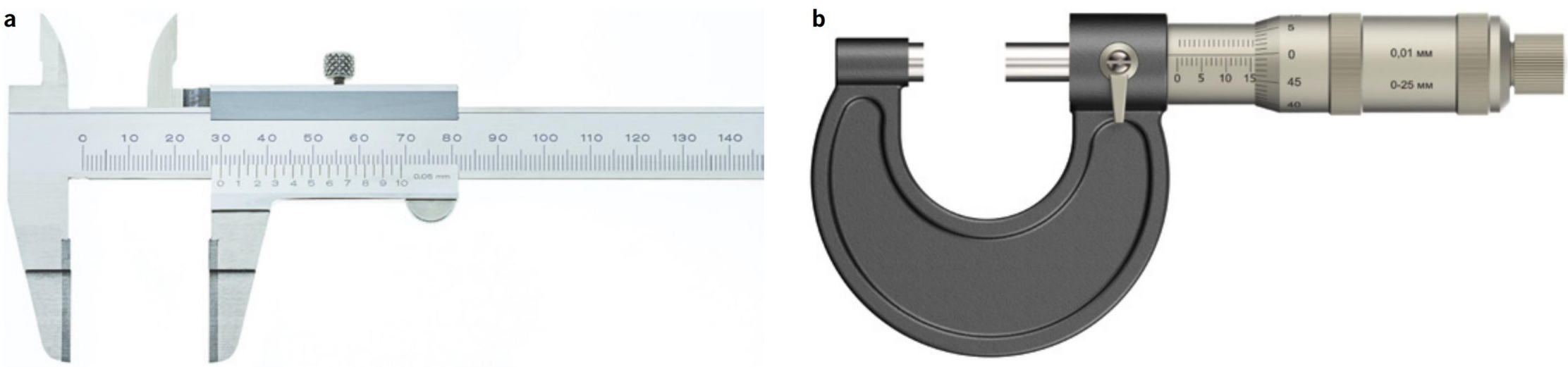


FIGURE 1.5.6 (a) A Vernier calliper and (b) micrometer use screws to determine the measurement.

Uncertainties and errors should always be calculated or measured and then reported. They then form part of the analysis and interpretation (see Module 1.7 Data analysis) as well as the evaluation. Also, it is a good idea to consider uncertainty and error when planning experiments (see Part B: Student experiment).

SKILLBUILDER 1.5.1

Calculating absolute measurement uncertainty

Calculate the absolute measurement uncertainty for instrumental error during an experiment where the temperature was measured at 32°C using a glass thermometer with increments of 1°C and also a digital thermometer with increments of 0.1°C.

For the glass thermometer

For analog instruments, the absolute measurement uncertainty is equal to half the smallest increment.

1 Write the formula.

$$\text{uncertainty} = \pm\frac{\text{smallest increment}}{2}$$

2 Insert the values and calculate.

$$\text{uncertainty} = \pm\frac{1}{2}$$
$$= \pm 0.5°\text{C}$$

3 Combine the measurement with the uncertainty.

32°C ± 0.5°C

For the digital thermometer

For digital instruments, the absolute measurement uncertainty is equal to the smallest decimal place displayed.

1 Write the formula.

uncertainty = smallest increment

2 Insert the values and calculate.

uncertainty = 0.1

3 Combine the measurement with the uncertainty.

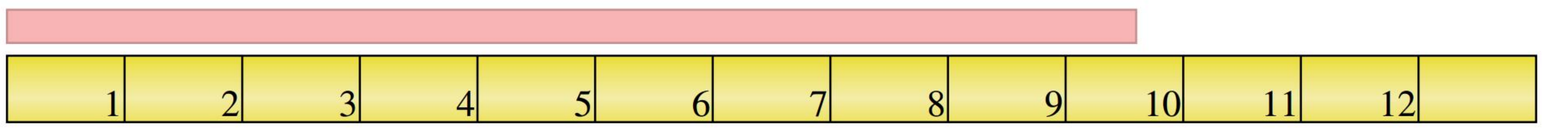
32.0°C ± 0.1°C

Worked example 1.5.1

READING MEASUREMENTS

For each of the following objects, determine its measurement and uncertainty.

a The length of the pink rectangle is measured with a ruler calibrated in cm.



Thinking	Working
The pink rectangle is between 9 cm and 10 cm in length, so the best estimate for this is 9.6 cm.	Length $L = 9.6$ cm
The limit of reading is 1.0 cm so this is the uncertainty in a cm ruler.	$\Delta L = \pm 1.0$ cm
Write the measurement and the uncertainty.	Length = 9.6 ± 1.0 cm

b The temperature of tap water is measured using an analog thermometer.

Thinking	Working
The temperature is between 40.1°C and 40.2°C, with the best estimate of 40.14°C.	Temperature $T = 40.14$°C
The limit of reading is 0.1°C so the uncertainty is half of this: 0.05°C.	$\Delta T = \pm 0.05$°C
Write the measurement and uncertainty.	$T = 40.14 \pm 0.05$°C

c The temperature of a bucket of tap water is measured using a digital thermometer.

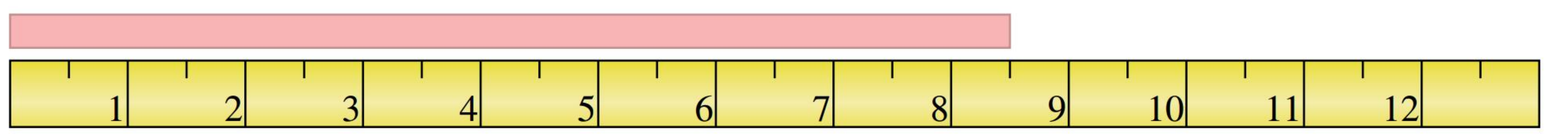
Thinking	Working
This temperature measurement is done using a digital thermometer, so the temperature is simply read off the screen at 36.4°C.	Temperature $T = 36.4°C$
The uncertainty in this measurement is then 1 of the smallest decimal value: ± 0.1°C.	$\Delta T = \pm 0.1°C$
Write the measurement and uncertainty.	$T = 36.4 \pm 0.1°C$

➤ Try yourself 1.5.1

READING MEASUREMENTS

For each of the following objects, determine its measurement and uncertainty.

a The length of the pink rectangle is measured with a ruler calibrated in half-cm intervals.



b The volume of the liquid is measured in a measuring cylinder calibrated in mL.

c The mass of this apple is measured on an electronic balance.

Determining an uncertainty in several trials of a measurement

The information above described how to determine the absolute uncertainty in a single measurement. To reduce the absolute uncertainty of a measurement, take as many trials as possible of the same measurement.

Once a series of trials of a single measurement has been taken, the best estimate of the value of the quantity is the average, or mean:

$$x_{\text{best}} = \bar{x} = \frac{\text{sum of the individual trials, } x_1, x_2, \ldots}{\text{number of trials, } n} = \frac{\sum x}{n}$$

The **absolute uncertainty of the mean**, $\Delta\bar{x}$, is found by finding the difference between the smallest and largest individual trials, then dividing by 2:

$$\Delta\bar{x} = \pm\left(\frac{x_{\text{max}} - x_{\text{min}}}{2}\right)$$

Note that if the absolute uncertainty of the mean gives a smaller value than the individual absolute uncertainties, then the absolute uncertainty of the mean should be the absolute uncertainty of the individual measurements.

$$\text{uncertainly} = \pm\frac{\text{upper value} - \text{lowest value}}{2}$$

For a series of trials of a single measurement, the best estimate of the measurement is the mean, or average, and the best estimate of its uncertainty is the absolute uncertainty of the mean.

Worked example 1.5.2

CALCULATING UNCERTAINTY

The thickness, t, of a copper wire was measured along six points and recorded in mm (using a micrometer with an uncertainty of ± 0.01 mm) as:

5.84, 5.83, 5.82, 5.85, 5.79, 5.81

Calculate the mean (average) value for the thickness of the copper wire and its absolute uncertainty.

Thinking	Working
First, calculate the mean of the set of measurements.	$t = \frac{5.84 + 5.83 + 5.82 + 5.85 + 5.79 + 5.81}{6}$ $= \frac{34.94}{6}$ $= 5.82\text{mm}$
Write down the formula for absolute uncertainty.	$\Delta\bar{x} = \pm\left(\frac{x_{\text{max}} - x_{\text{min}}}{2}\right)$
Substitute into the formula to find the uncertainty in the mean.	$\Delta t = \pm\left(\frac{5.85 - 5.79}{2}\right)$ $= \pm\left(\frac{0.06}{2}\right)$ $= \pm 0.03\text{ mm}$
This value is larger than each individual uncertainty (0.01), so it will now be the final absolute uncertainty of the mean. Combine the mean and the uncertainty in the final answer.	$t = 5.82 \pm 0.03\text{mm}$

➤ Try yourself 1.5.2

CALCULATING UNCERTAINTY

The masses, *m*, of five pendulum bobs taken from the same batch were measured using an electronic balance set to grams:

24.66 g, 24.59 g, 24.51 g, 24.76 g, 24.75 g

Calculate the mean (average) mass of the pendulum bobs and the absolute uncertainty in the mean.

Calculating percentage error in values

As stated above, scientist try to calculate the 'true' or 'correct' value. However, due to uncertainties in the measurements experimental results may result in an inaccurate value. The density of water is generally stated to be 1 kg m^{-3}; however, the exact density at 4.0 °C is 0.9998395 kg m^{-3}.

The difference between the true value and the generally accepted value can be calculated using the percentage error formula, as shown in worked example 1.5.2.

In this case the measured value is replaced with the accepted value. The percentage error in the accepted (rounded) value of 1 kg m^{-3} is less than 0.02%. This indicates that using 1 kg m^{-3} is acceptable since the percentage error is very small and likely to be much smaller than experimental uncertainty.

Percentage uncertainty

The absolute uncertainty of a measurement expresses the uncertainty in the readings. This reflects the precision of the measurement.

Measurements are quantified by associating them with uncertainty. For example, the best estimate of a volume is 5.0 cm^3, but due to uncertainty, the volume might be as small as 4.9 cm^3 or as large as 5.1 cm^3. In this example, the absolute uncertainty in the volume is ±0.1 cm^3.

Uncertainty can also be reported as a percentage of the measurement; this is known as **percentage uncertainty**. To calculate the percentage uncertainty, apply this formula:

$$\text{percentage uncertainty (\%)} = \left(\frac{\text{absolute uncertainty}}{\text{measurement}}\right) \times 100\%$$

It is important to not confuse percentage uncertainty with percentage error which was introduced at the beginning of module 1.5. Percentage error expresses the difference between the measured value and the accepted value. This reflects the accuracy of the measurement. Unlike percentage uncertainty, which can be determined for any measurement, percentage error can only be determined if an accepted value (such as the speed of light) is known.

$$\text{percentage error (\%)} = \left|\frac{\text{measured value} - \text{true value}}{\text{true value}}\right| \times 100\%$$

ℹ The percentage uncertainty is a way of writing the uncertainty of a measurement as a percentage of the measurement.

ℹ The percentage uncertainty reflects the precision of a measurement, that is, how far it is from other measurements of the same thing. The percentage error reflects the accuracy of a measurement, that is, how far it is from an established or true value.

Worked Example 1.5.3

CALCULATING PERCENTAGE UNCERTAINTY FOR INSTRUMENTAL ERROR

The temperature during an experiment was measured and then reported at 32.00°C ± 0.05°C. Calculate the percentage uncertainty.	
Thinking	**Working**
Write the formula for percentage uncertainty.	$\text{percentage uncertainty (\%)} = \pm\left(\frac{\text{absolute uncertainty}}{\text{measurement}}\right)\times 100\%$
Insert the values and calculate.	$\text{percentage uncertainty (\%)} = \pm\left(\frac{0.05}{32}\right)\times 100\%$ $= 0.16\ \%$
Combine the measurement with the percentage uncertainty and express to the appropriate number of significant figures.	32.00°C ± 0.16%

➤ Try yourself 1.5.3

CALCULATING PERCENTAGE UNCERTAINTY FOR INSTRUMENTAL ERROR

A ray of light was bent through a prism by an angle of 11.4 ± 0.6 degrees. Calculate the percentage uncertainty.

Significant figures

Another way of describing precision is by the number of **significant figures** in a measurement. The significant figures of a measurement are digits that are known exactly. The more significant figures a measurement has, the higher its precision.

When measuring phenomena during experimentation, the precision of the instruments determines the number of significant figures and decimal places you record in the data. Significant figures convey meaning and precision, and the number of significant figures used depends on the scale of the instrument. You should record data using the number of significant figures available from the equipment or observation. Using either a greater or smaller number of significant figures is misleading. Significant figures are the exact digits observed when recording the results of an observation or experiment. For example, if the distance travelled by an object in 20 seconds was 6.0 m because exactly 6.0 m was observed, then the measurement is 6.0 m with 2 significant figures, not 6 m. Table 1.5.3 shows some examples of measurements and how many significant figures they have.

TABLE 1.5.3 Measurements and significant figures (significant figures shown in bold)

Measurement	Number of significant figures
4.2003 $\times 10^{-5}$	5
1.9 $\times 10^{23}$	2
3.500 $\times 10^{2}$	4
6 $\times 10^{24}$	1
15	2
3.5	2
3.50	3
0.0**37**	2
1401	4
1400	2

> It is important to record the exact numbers measured during an experiment. This determines the significant figures, and later the accuracy and precision of the analysis. If a zero is observed, record it, as it is the exact amount measured. This includes all zeros before and after decimal places.

Using either a greater or smaller number of significant figures can be misleading. For example, Table 1.5.4 shows three measurements to 2 decimal places (4 significant figures). The data was entered into a spreadsheet to calculate the mean, which was displayed with 3 decimal places. You would record the mean as 19.52 mL, not 19.517 mL, because 2 decimal places is the precision limit of the instrument. Recording 19.517 g would be an example of false precision.

TABLE 1.5.4 An example of false precision in a data calculation

Trial	1	2	3	Mean
Volume (mL)	19.45	19.55	19.55	19.517

When writing an answer to the correct number of significant figures, you may need to use rounding if the initial answer has more figures (digits) than you need. These extra figures are called 'non-significant figures'. If the first non-significant figure is ≥5, round up the number. If the first non-significant figure is <5, then do not round up. For example, if the initial answer for a calculation was 2.1259 but you only needed an answer to 3 significant figures, you would round it to 2.13. If the initial answer was 2.1241, then to 3 significant figures, this becomes 2.12.

SKILLBUILDER 1.5.2

Identifying significant figures

When giving an answer to a calculation, it is important to take note of the number of significant figures that you use.

You should give an answer that is as accurate as possible. However, an answer cannot be more accurate than the data or the measuring device used to calculate it. For example, if an electronic balance that measures to the nearest gram shows that an object has a mass of 56 g, then the mass should be recorded as 56 g, not 56.0 g. This is because you do not know whether it is 56.0 g, or 56.1 g, or 56.2 g or 55.8 g.

The number 56 has 2 significant figures. Recording to 3 significant figures (e.g. 56.0 g or 55.8 g) would not be scientifically 'honest'.

If this mass of 56 g is used to calculate another value, it would also not be 'honest' to give an answer that has more than 2 significant figures.

Determining the number of significant figures to give an answer to depends on the kind of calculation you are doing.

- If you are multiplying or dividing, use the smallest number of significant figures provided in the initial values.
- If you are adding or subtracting, use the smallest number of decimal places provided in the initial values.

Working out the number of significant figures

Use the following rules to avoid confusion in determining how many significant figures are in a number.

- All digits (including 0) in the coefficient of a number written in scientific notation are significant.
- All non-zero digits are always significant; for example, 21.7 has 3 significant figures.
- All zeros between two non-zero digits are significant; for example, 3015 has 4 significant figures.
- A zero to the right of a decimal point and following a non-zero digit is significant; for example, 0.5700 has 4 significant figures.
- Any other zero is not significant, as it will be used only for locating decimal places; for example, 0.005 has just 1 significant figure.

Worked example 1.5.4

IDENTIFYING SIGNIFICANT FIGURES

Determine how many significant figures there are in these measurements.

a 8.07×10^{14} kg

b 9.00 m

c 0.000 100 3 s

d 4560 N

Thinking	Working
a This measurement is written in scientific notation; therefore, all digits in the coefficient are significant.	3 significant figures
b The final zeros are significant, as they did not need to be written down unless they were specifically measured.	3 significant figures
c The first four zeros are not significant as they are just placeholders. The middle zeros are significant because they are located between two non-zero digits.	4 significant figures
d The final zero is not significant, or is ambiguous, so it is not counted.	3 significant figures

➤ Try yourself 1.5.4

SIGNIFICANT FIGURES

Determine how many significant figures there are in these measurements.

a 77 000 T

b 0.000 000 422

c 2.76×10^{-17} C

d 20.040 m s^{-2}

Calculations with uncertainties

There are a few rules when conducting calculations with numbers (or measurements) that have uncertainties. It is important to record the correct uncertainty once all the calculations are done so that the appropriate accuracy is reported. Table 1.5.5 outlines the rules for undertaking calculations with data and its associated uncertainty.

Keep in mind that the rules for significant figures apply to all numerical reporting, including the uncertainties.

TABLE 1.5.5 Rules for calculations involving uncertainty

Calculation	Rule	Examples
addition and subtraction	add the absolute uncertainties	$5.4 \pm 0.05 + 3.2 \pm 0.05 = 8.6 \pm 0.1$ $5.4 \pm 0.05 + 3.2 \pm 0.1 = 8.6 \pm 0.15$ $5.4 \pm 0.05 - 3.2 \pm 0.05 = 2.2 \pm 0.1$ $5.4 \pm 0.05 - 3.2 \pm 0.1 = 8.6 \pm 0.15$
multiplication and division	add the percentage uncertainties	$3.0 \pm 0.05 \times 1.5 \pm 0.05$ $= 3.0 \pm 1.6\% \times 1.5 \pm 3.3\% = 4.5 \pm 4.9\%$ $3.0 \pm 0.05 \div 1.5 \pm 0.05$ $= 3.0 \pm 1.6\% \div 1.5 \pm 3.3\% = 2.0 \pm 4.9\%$
multiplying by a constant (absolute uncertainty)	multiply the uncertainty	$3.14 \times (4.1 \pm 0.05) = 12.9 \pm 0.16$
multiplying by a constant (percentage uncertainty)	maintain the uncertainty	$3.14 \times (4.1 \pm 1.6\%) = 12.9 \pm 1.6\%$
exponents	multiply the percentage uncertainty by the absolute value of the exponent	$(2.20 \pm 0.05)^2 = (2.20 \pm 2.2727\%)^2$ $= 4.84 \pm (2 \times 2.2727)\% = 4.84 \pm 4.54\%$ $= \sqrt{6.25 \pm 0.01} = \sqrt{6.25 \pm 0.16\%}$ $= 2.5 \pm (0.5 \times 0.16\%) = 2.5 \pm 0.08\%$

Note that addition, subtraction, multiplication, division, powers and square roots are the only operations that require you to work out the uncertainties. Other functions such as sin, cos and tan require the use of calculus, so you will not need to directly calculate the uncertainties of these operations in this course.

When propagating uncertainties with a mixture of addition, subtraction, multiplication, division and exponents, perform the addition and subtraction calculations first, then the multiplication, division and power calculations.

Worked example 1.5.5

ADDING OR SUBTRACTING UNCERTAINTIES

Perform the following calculation: $(2.6 \pm 0.5)\,\text{cm} + (2.8 \pm 0.5)\,\text{cm}$	
Thinking	**Working**
First ignore each uncertainty and add the measurements.	Let x be the sum of the two quantities. $x = 2.6 + 2.8 = 5.4\,\text{cm}$
This is an addition operation, so add the absolute uncertainties.	$\Delta x = 0.5 + 0.5 = 1.0\,\text{cm}$
The absolute uncertainty can have 2 significant figures here because the first digit is 1. The absolute uncertainty also has 1 decimal place so x will also have 1 decimal place.	$x = 5.4 \pm 1.0\,\text{cm}$

➤ Try yourself 1.5.5

ADDING OR SUBTRACTING UNCERTAINTIES

Perform the following calculation:
$(4 \pm 2)\,\text{N} - (5.33 \pm 0.05)\,\text{N}$

Worked example 1.5.6

MULTIPLYING OR DIVIDING UNCERTAINTIES

Perform the following calculation: $(6.2 \pm 0.5)\,\text{cm} \times (2.81 \pm 0.01)\,\text{cm}$		
Thinking	**Working**	
First ignore each uncertainty and multiply the measurements. Do not forget to operate on the units as well.	Let x be the product of the two quantities: $x = 6.2 \times 2.81 = 17.422\,\text{cm}^2$	
This is a multiplication operation, so the absolute uncertainties will need to be converted into percentage uncertainties.	$6.2 \pm 0.5\,\text{cm}$ $= 6.2 \pm \frac{0.5}{6.2} \times 100\%\,\text{cm}$ $= 6.2 \pm 8.06\%$	$2.81 \pm 0.01\,\text{cm}$ $= 2.81 \pm \frac{0.01}{2.81} \times 100\%\,\text{cm}$ $= 2.81 \pm 0.356\%$
The percentage uncertainties are now added.	$\Delta x\% = 8.06\% + 0.356\% = 8.416\%\,\text{cm}^2$	

And the percentage uncertainty is now converted back into an absolute uncertainty.	$\Delta x\% = 8.416\%$ of $17.422\,\text{cm}^2$ $= 8.416 \times 17.422$ $= 1.5\,\text{cm}^2$
The absolute uncertainty has 1 as its first digit, therefore one more digit can be quoted: $\Delta x = 1.5$. The absolute uncertainty also has 1 decimal place so x will also have 1 decimal place.	$x = 17.4 \pm 1.5\,\text{cm}^2$

➤ Try yourself 1.5.6

MULTIPLYING OR DIVIDING UNCERTAINTIES

Perform the following calculation:

$$\frac{(2.0 \pm 0.2)\,\text{cm}}{(3.0 \pm 0.6)\,\text{s}}$$

Worked example 1.5.7

MIXED UNCERTAINTY CALCULATIONS

If $a = 4.52 \pm 0.02\,\text{m}$ and $b = 2.0 \pm 0.2\,\text{s}$, then calculate c and its uncertainty when $c = a^2b^3$.

Thinking	Working
First, ignore each uncertainty and perform the calculation for c. Don't forget the units.	$c = 4.52^2 \times 2.0^3$ $= 163.4432\,\text{m}^2\text{s}^3$
This is a multiplication operation, so the absolute uncertainties need to be converted into percentage uncertainties.	$a = 4.52 \pm 0.02\,\text{m}$ $\quad b = 2.0 \pm 0.2\,\text{s}$ $= 4.52 \pm \frac{0.02}{4.52} \times 100\%\,\text{m}$ $\quad = 2.0 \pm \frac{0.2}{2.0} \times 100\%\,\text{s}$ $= 4.52 \pm 0.4425\%\,\text{m}$ $\quad = 2.0 \pm 10\%\,\text{s}$
To obtain the final percentage uncertainty, the individual percentage uncertainties are multiplied by the powers of a and b given in the formula.	$\Delta c\% = 2 \times 0.4425\% + 3 \times 10\%\,\text{m}^2\,\text{s}^3$ $= 0.885\% + 30\%\,\text{m}^2\,\text{s}^3$ $= 30.885\%\,\text{m}^2\,\text{s}^3$
Now convert the percentage uncertainty into an absolute uncertainty.	$\Delta c = 30.885\%$ of 163.4432 $= \frac{30.885}{100} \times 163.4432$ $= 50.48\,\text{m}^2\,\text{s}^3$
The absolute uncertainty does not have 1 as its first digit, therefore it must be rounded to 1 significant figure: $\Delta c = 50$. The absolute uncertainty therefore is written to the 10 s placeholder, so c will also be written to the nearest 10 s placeholder. An alternative to this is to write c and its uncertainty to the same power of 10.	$c = 160 \pm 50\,\text{m}^2\,\text{s}^3$ $= (1.6 \pm 0.5) \times 10^2\,\text{m}^2\,\text{s}^3$

➤ Try yourself 1.5.7

MIXED UNCERTAINTY CALCULATIONS

If $a = 3.6 \pm 0.6\,\text{m}$, $b = 9.91 \pm 0.01\,\text{m}$, and $c = 4.9 \pm 0.5\,\text{kg}$, calculate d when $d = \frac{a+b}{\sqrt{c}}$.

1.5 Review

SUMMARY

- All measurements made in physics experiments are subject to a level of uncertainty, or doubt, to the precision of that measurement.
- Systematic errors arise due to mistakes in calibrating or using equipment the wrong way for every measurement.
- Random errors are naturally occurring and cannot be eliminated.
- Accuracy is a description of how close a measurement is to an accepted value. To obtain accurate results, you must minimise systematic errors.
- Precision is a description of how close together a group of measurements are. To obtain precise results, you must minimise random errors.
- Uncertainty is a range of measurements from the experiment in which the true value is thought to be. A measurement without an uncertainty is meaningless.
- Error is the difference between a measurement and the true value; this is *not* an indication of human error or a mistake.
- Uncertainty and error values are presented as a range (e.g. ±0.3) or a percentage (±1.6%)
- The limit of reading of an instrument is the smallest graduation on the device.
- Analogue instruments with a single scale reading have an absolute measurement uncertainty equal to half the limit of reading. Analogue instruments with a double scale reading have an absolute uncertainty equal the limit of reading.
- Digital instruments have an absolute uncertainty equal to the limit of reading (the smallest decimal place displayed).
- The uncertainty in the average of several trials is given by:

$$\text{uncertainty} = \pm\frac{\text{upper value} - \text{lowest value}}{2}$$

$$\text{absolute uncertainty} = \pm\frac{\text{smallest increment}}{2}$$

$$\Delta\bar{x} = \pm\left(\frac{x_{max} - x_{min}}{2}\right)$$

- Percentage uncertainty is an indicator of precision. Percentage error is an indicator of accuracy and can only be applied when a theoretical or accepted result is known.
- Percentage uncertainty is given by:

$$\text{percentage uncertainty (\%)} = \pm\left(\frac{\text{absolute uncertainty}}{\text{measurement}}\right)\times 100\%$$

- Percentage error is given by:

$$\text{percentage error (\%)} = \left|\frac{\text{measured value} - \text{true value}}{\text{true value}}\right|\times 100\%$$

- Significant figures are a way of communicating how precise a measurement is.
- The number of significant figures used depends on the scale of the instrument.
- There are specific rules governing how many significant figures there can be in any measurement.
  - All digits (including 0) in the coefficient of a number written in scientific notation are significant.
  - All non-zero digits are always significant.
  - All zeros between two non-zero digits are significant.
  - A zero to the right of a decimal point and following a non-zero digit is significant.
  - Any other zero is not significant.
- Propagation of uncertainties involves the mathematical combination of uncertainties from a range of variables.
- When adding or subtracting measurements, the individual absolute uncertainties always add.
- When multiplying or dividing measurements, the individual percentage uncertainties always add.
- When raising a measurement to a power, the percentage uncertainty is multiplied by the absolute value of the power.
- When using measurements in a formula, perform any addition and subtraction propagations first, followed by multiplication, division and exponents.

KEY QUESTIONS

Describe

1 State the type of error associated with:

a inaccurate measurements

b imprecise measurements.

2 Identify whether each of the situations below is a mistake, a systematic error or a random error.

a A student measured the lengths of three different wires using a cm ruler but did not check that the wire was lined up at the zero mark on the ruler.

b A student was measuring the mass of approximately 2 g samples of 5-cent pieces using a balance that was accurate to the nearest 1 g.

c A student sometimes forgot to rezero the balance between weighing trolleys used in a motion experiment.

3 State the absolute uncertainty of the following instruments:

a a cm ruler

b a protractor graduated in degree intervals

c an electronic balance giving a reading down to the nearest 0.001 g

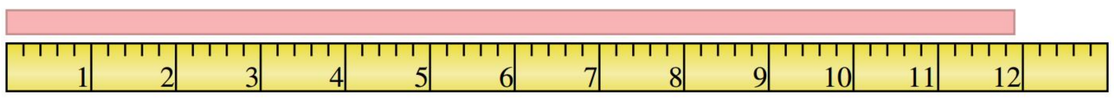
d an analog needle voltmeter graduated in 10 volt intervals.

Apply

4 Explain why it would be unreasonable to state that the absolute uncertainty in a handheld stopwatch is ± half of the limit of reading, or ± 0.005 s.

5 Explain why repeated measurements do not change the systematic error.

6 Determine the length, and absolute uncertainty, of the pink rectangle using the given scale calibrated in cm.



7 Write the following measurements and uncertainties to the correct number of significant figures and decimal places:

a $(9.11 \times 10^{-31}) \pm (2.2345 \times 10^{-31})$ kg

b $(0.0023456 \pm 1.623 \times 10^{-4})$ s.

Analyse

8 Calculate the average and uncertainty of the two sets of data below.

Data set A: 11.4, 10.9, 11.8, 10.6, 11.5, 11.1

Data set B: 25.3, 27.4, 22.0, 26.1, 28.4, 23.1

9 Differentiate between precision and accuracy.

10 A friend asks to borrow your precious diamond for a day to show her family. You are a bit worried, so you carefully weigh your diamond on a scale that reads 8.17 g. The scale's precision is claimed to be ±0.05 g. The next day you weigh the returned diamond again, getting 8.09 g. Determine if this is your diamond.

11 The electrical power, P, dissipated by a resistor in an electrical circuit is given by:

$P = I^2 R$

where

I is the current (A)

R is the resistance (Ω).

If the percentage uncertainty in I is ±7% and the percentage uncertainty in R is ±10%, calculate the percentage error in P.

12 If $a = 20.0 \pm 0.5$ m and $b = 5 \pm 1$ m, calculate the value and absolute uncertainty of $c = 2a - b$.

13 Calculate C and ΔC, if $C = 2\pi r$ and $r = 4.12 \pm 0.05$ m.

14 The density of an object is found by dividing its mass by its volume. An iron cube had its side length and mass measured five times.

Mass (±0.01 g)	121.37	121.40	121.39	121.36	121.38
Side length (±0.05 cm)	2.47	2.49	2.48	2.47	2.50

Calculate the following values, including the absolute uncertainty:

a average mass

b average side length

c volume of the cube

d density of the cube.

1.6 Tables and graphing

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- create tables to record and organise data
- appreciate that graphs can show a wealth of information relating two or more variables and constants, including their uncertainties
- understand that graphs can be used to predict relationships between variables or used to find outliers in data
- recognise the common types of graphs or relationships seen in physics and know examples of each.

PRESENTING DATA IN TABLES

Tables record number values and allow you to organise your data. In general, tables provide more detailed data than graphs, but it is easier to observe trends and patterns in data when they are in graph form than when they are in table form.

Presenting raw data in tables

Tables organise data into rows and columns, and can vary in complexity according to the nature of your data. Tables can be used to organise raw data and **processed data**, or to summarise results. The first column of a table should contain the independent variable (the one you control) subsequent columns should contain trials of the dependent variable (the one that may change in response to a change in the independent variable).

As you can see in Figure 1.6.1, tables should have the following features:

- a descriptive title
- column headings (including the units)
- aligned figures (align the decimal points)
- the independent variable placed in the left column.

Table 1: Neutralisation of excess acid from the reaction of HCl with 1.2 g of calcium carbonate

	volume of 0.5 M NaOH (mL)			
concentration of HCl (M)	**trial 1**	**trial 2**	**trial 3**	**average**
0.1				
0.3				
0.5				
0.7				
1.0				
2.0				

accurate descriptive title

dependent variable identifies the data set and shows the unit of measurement

independent variable in the left-hand column shows the units of measurement

rows show the different concentrations of the solution used—the range of values for the independent variable

a minimum of five different data points for the independent variable

space for trials—in this case three repeat trials were conducted

column to calculate the averages

FIGURE 1.6.1 Features of a good table

PRESENTING DATA IN GRAPHS

A **graph** is an incredibly useful tool. In physics, data is plotted using a line or curved graph and it is sometimes called a scatterplot.

Plotting data in graphs has many advantages.

- Data can be represented visually.
- Data points that are deemed to be outliers can be ignored.
- Constants can be determined from the properties of the line or curve.
- Uncertainties can be represented as **error bars**.
- A general **line of best fit** that matches the trend of the majority of the data points can be determined.
- The uncertainty in the gradient and intercept can be propagated using a line of minimum fit and a line of maximum fit (see 1.7 Data analysis).
- Any known relationship between the dependent and independent variables can be supported or rejected, especially by the use of uncertainties.

Tables often provide more detailed data than graphs, but graphs can suggest a possible relationship between the dependent and independent variables, and highlight if none exists. From the shape of the curve, it is easier to observe trends, patterns and gaps in data in graphical form than in tabular form.

Graphs, like that shown in Figure 1.6.2, are used when two variables are being considered and one variable is dependent on the other. The graph shows the relationship between the variables.

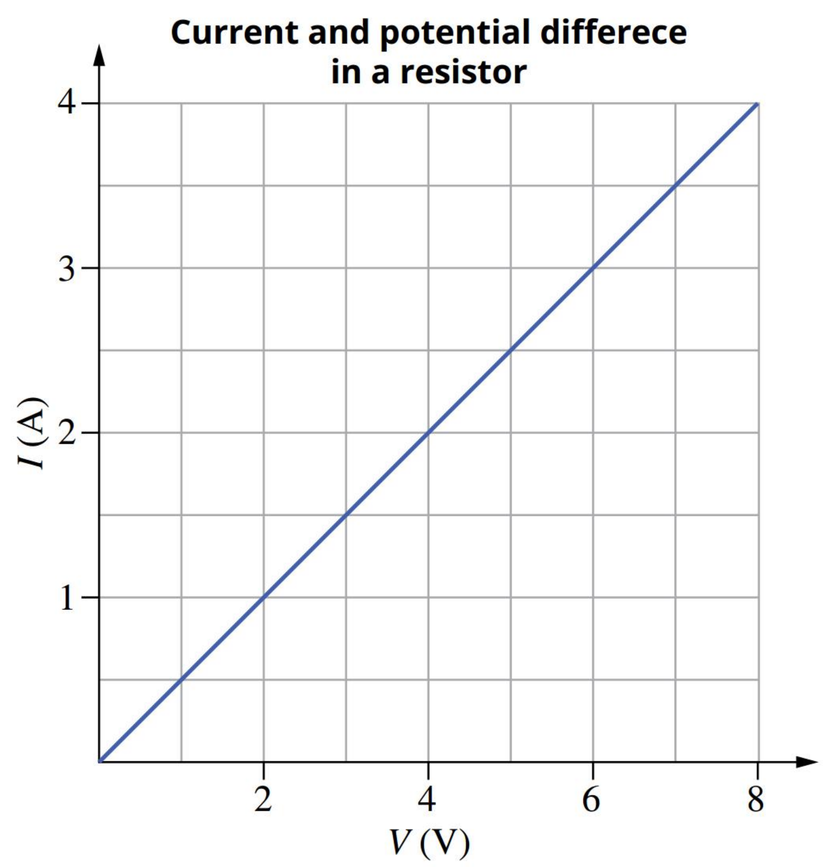


FIGURE 1.6.2 A graph showing the relationship between two variables: current (dependent variable) and voltage (independent variable)

DRAWING GRAPHS IN PHYSICS

For use in physics, every graph must have the following features:

1 The graph must have a suitable set of axes for the independent and dependent variables.

Most physics graphs are only drawn in the first quadrant, but some graphs use all four quadrants (i.e. have negative values for the independent and dependent variables).

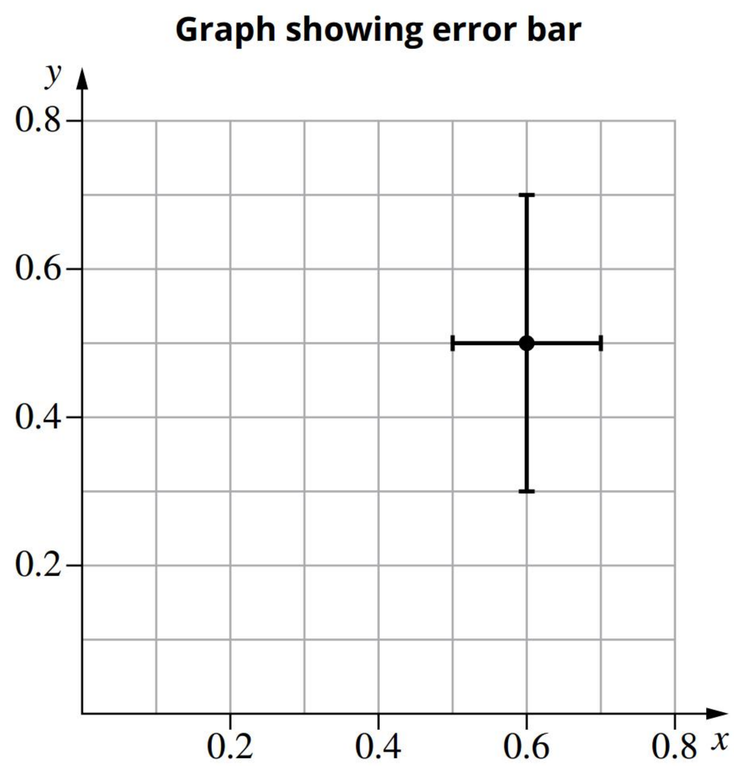


FIGURE 1.6.3 This error bar has an x value of 0.6 ± 0.1 and a y value of 0.5 ± 0.2.

Error bars are the graphical representation of the uncertainties in the independent and dependent variables.

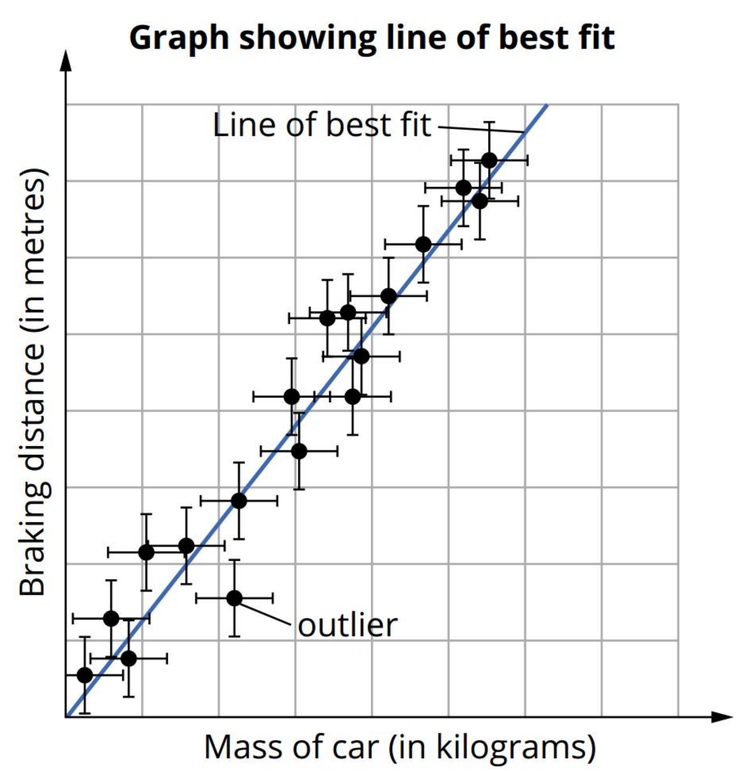


FIGURE 1.6.4 This graph shows that the line of best fit should normally pass through the error bars of each point and be extrapolated so that it intersects the y-axis.

The line of best fit is a straight line or curved line that best summarises the general pattern of the data on the graph.

Remember that:

- the independent variable is the variable that you deliberately change and always goes along the x-axis
- the dependent variable is the variable that changes and always goes on the y-axis.

2 The graph must have a suitable scale that allows information to be seen easily and quickly.

For most graphs, it is important to choose a scale that is linear and has tick marks at common intervals (e.g. 2, 5, 10, 100 units).

3 The title and axes must have labels. Make sure that the axis labels show information about the quantity and units. Give a descriptive title that is not just a repeat of the labels of the axes.

4 Data points should be plotted as a small circle or small cross indicating their position.

5 Error bars should be drawn for each point. These indicate the absolute uncertainties in the independent (a horizontal line) and dependent (a vertical line) values. They are drawn as a horizontal line centred on the data point indicating the independent variable's uncertainty left and right of the value, and as a vertical line centred on the data point above and below the value, indicating the dependent variable's uncertainty. Combining the x and y error bars forms an error rectangle that the true measurement is located within (Figure 1.6.3).

The smaller the errors bars for a given point, the more precise the measurement is.

The line of best fit

The line of best fit, also known as a trend line, is the straight line or a curve that best summarises the data. This line does not have to pass through every point or the origin, but does have to be one smooth continuous line or curve and *not* a 'join the dots' line (Figure 1.6.4). Typically, the line of best fit should have as many points on the line as possible, but if this is not possible then it should have as many points above the line as there are below the line.

These are some of the general rules to follow when making a graph.

- Keep the graph simple and uncluttered.
- Use a descriptive title.
- Represent the independent variable on the x-axis and the dependent variable on the y-axis.
- Start each axis at zero.
- Match the length of the axes to the data.
- Clearly label axes with both the variable and the unit in which it is measured.
- Use small symbols such as circles or crosses for data points.
- Use different symbols for different data sets.

TYPES OF GRAPHS SEEN IN PHYSICS

There are several types of graphs, including line graphs and bar graphs. The best one to use will depend on the nature of the data. In physics, many relationships in the form of formulas and graphs are seen that exist between two variables. Each graph below shows some particular relationship between the independent and dependent variables that you will encounter at some stage during your Physics course.

Linear graphs

Straight line or linear graphs represent variables that have a constant rate of change and the power of each variable is 1. The gradient and y-intercept of a linear graph are calculated easily, as shown in Figure 1.6.5. The general equation of a straight line is:

$$y = mx + c$$

where

m is the gradient

c is the y-intercept.

Examples of linear relationships in physics include force against acceleration and momentum against velocity. Note that, if the y-intercept of the equation is zero, then the relationship between the x- and y-variables is said to be directly proportional and the equation is $y = mx$. The equation of the line in Figure 1.6.6 is $y = 2x$.

Linear graphs of the form $y = mx + c$ either increase (if the gradient is positive) at a constant rate, or decrease (if the gradient is negative) at a constant rate.

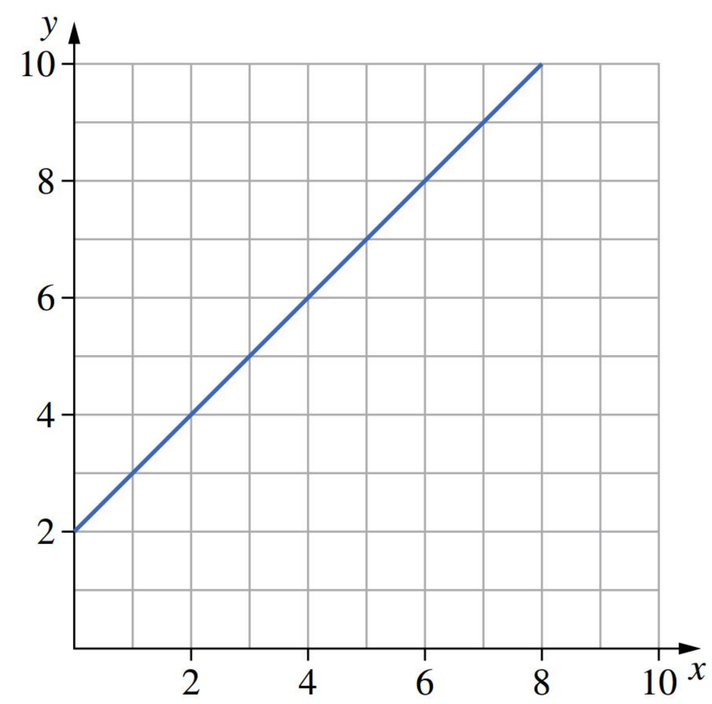


FIGURE 1.6.5 The linear, or straight line, graph. In this example, the equation of the line is $y = x + 2$, with a gradient of 1 and y-intercept of 2.

Parabolas

Parabolas represent relationships in which the independent variable is squared and the dependent variable increases at an increasing rate, as shown in Figure 1.6.7. The general equation of a parabola is:

$$y = kx^2$$

where k is a constant.

Examples of parabolic relationships in physics include kinetic energy against velocity and the position of a projectile against time, when launched at an angle to the horizontal.

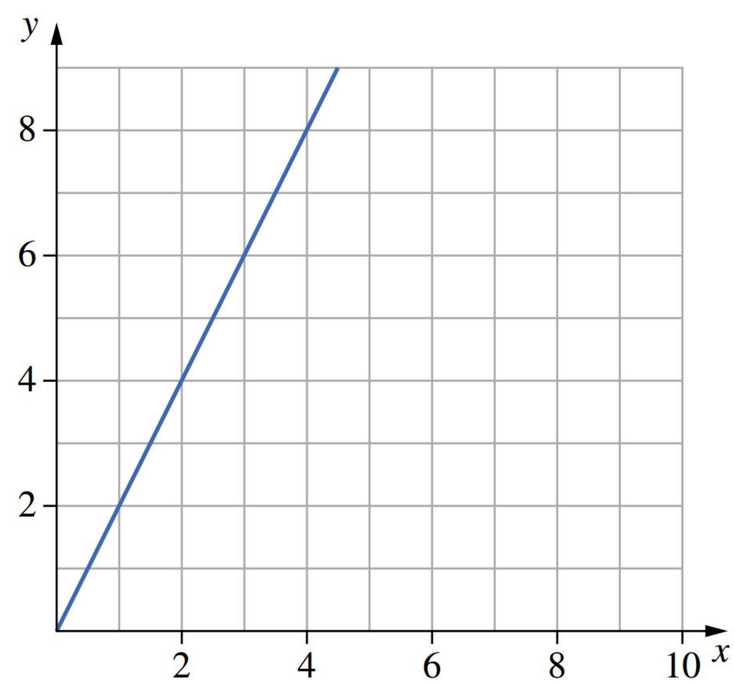


FIGURE 1.6.6 An example of a direct proportion. The equation of the line is $y = 2x$. The line passes through the origin and has a gradient of 2.

Inverse functions or hyperbolas

These graphs represent variables with an inverse or $\frac{1}{\text{independent variable}}$ relationship. The curves decrease at a decreasing rate and do not intersect the x- or y-axes. When one variable increases, the other variable decreases, as shown in Figure 1.6.8. The general equation of a hyperbola is:

$$y = \frac{k}{x}$$

where k is a constant.

Examples of hyperbolic relationships in physics include pressure against volume, and object distance against image distance for a lens.

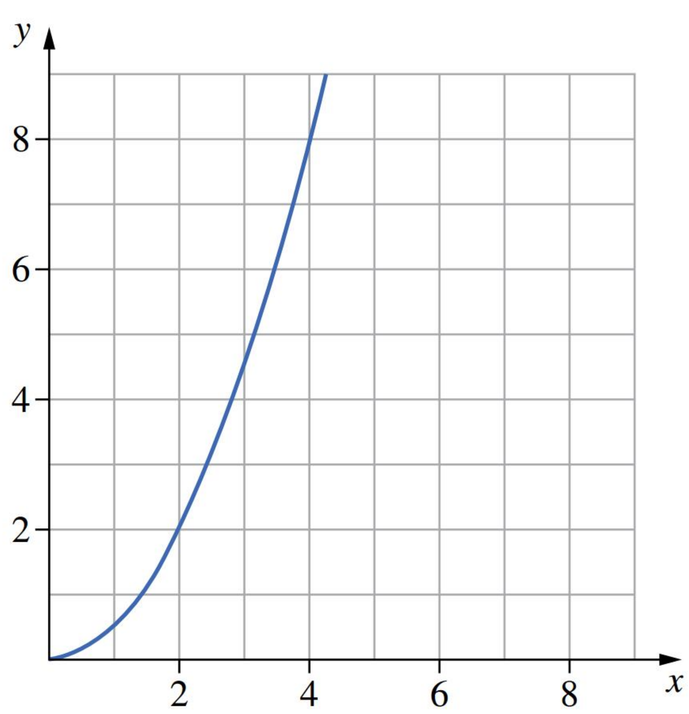


FIGURE 1.6.7 An example of a parabolic or squared graph. The equation of the parabola is $y = 0.5x^2$.

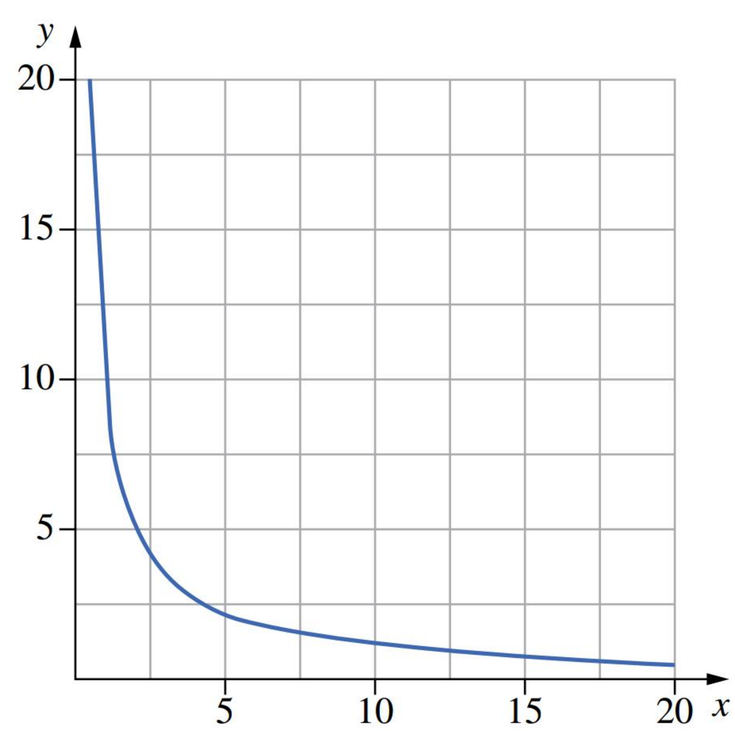


FIGURE 1.6.8 An example of a hyperbola, or inverse, graph. The equation of the hyperbola is $y = \frac{10}{x}$.

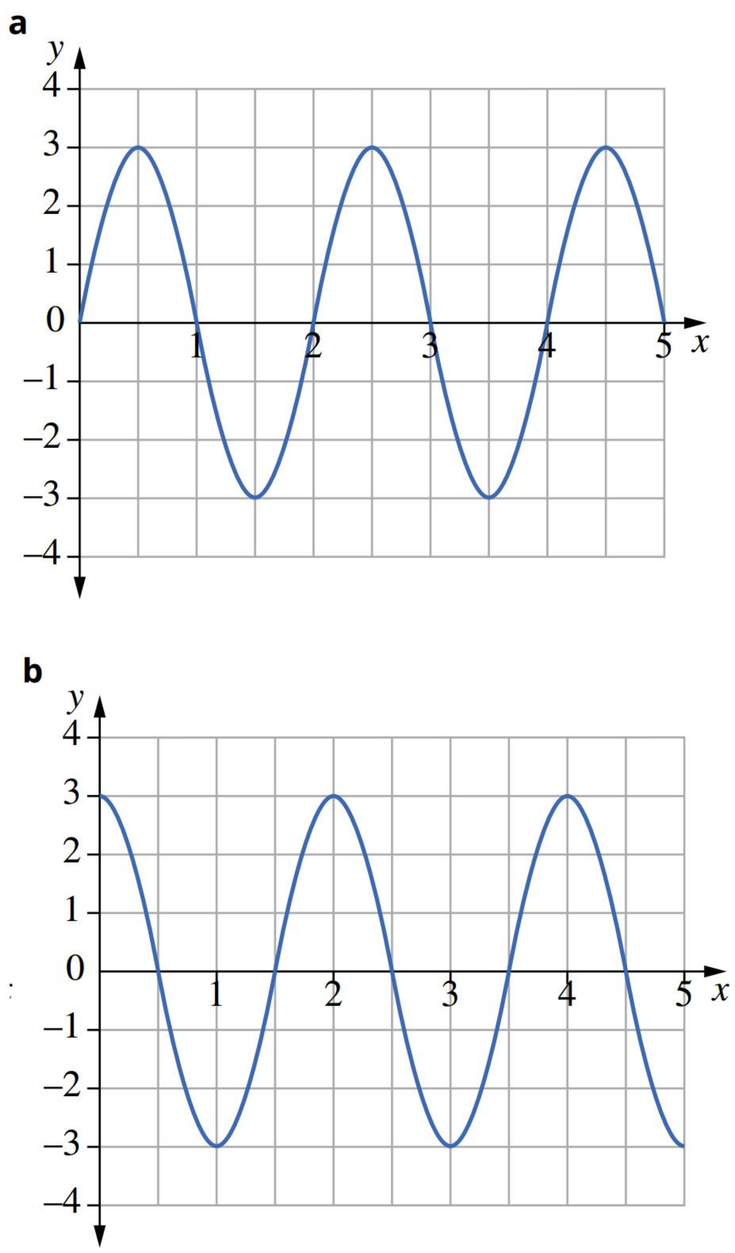


FIGURE 1.6.9 Examples of (a) a sine graph with equation $y = 3 \sin \pi x$ and (b) a cosine graph with equation of $y = 3 \cos \pi x$. The variable x is measured in radians in both cases.

Periodic or sine and cosine graphs

These graphs represent relationships that oscillate between a maximum and minimum value over a period of time, as shown in Figure 1.6.9. The general equations of a sine graph and a cosine graph are, respectively:

$$y = A \sin \omega x$$
$$y = A \cos \omega x$$

where

A is the amplitude, or the maximum value of y

ω is the angular frequency of the motion ($\omega = 2 \times \pi \times$ frequency).

Examples of sine and cosine relationships in physics include position versus time for a mass on a spring and current versus time for an alternating current supply.

Exponential decay

These graphs represent variables that decrease from an initial value over a period of time but never reach zero. The curves decrease at a decreasing rate, as shown in Figure 1.6.10. The equation of an exponential decay graph is:

$$y = Ae^{-kx}$$

where

A and k are constants

e is the mathematical constant 2.718 28…

Note that the exponential graph is different from an inverse relationship because an exponential relationship has a y-intercept, an inverse relationship does not.

An example of an exponential decay relationship in physics is the amount of decaying nuclear material remaining after a given time.

Square root graphs

These represent variables that increase but at a decreasing rate. This means that the dependent variable gets larger as the independent variable gets larger, but the difference becomes smaller and smaller. The equation for a square root graph (Figure 1.6.11) is:

$$y = k\sqrt{x}$$

where k is a constant.

Examples of where square root curves are used in physics are in the theoretical equation of the period of a pendulum and in many equations of relativity.

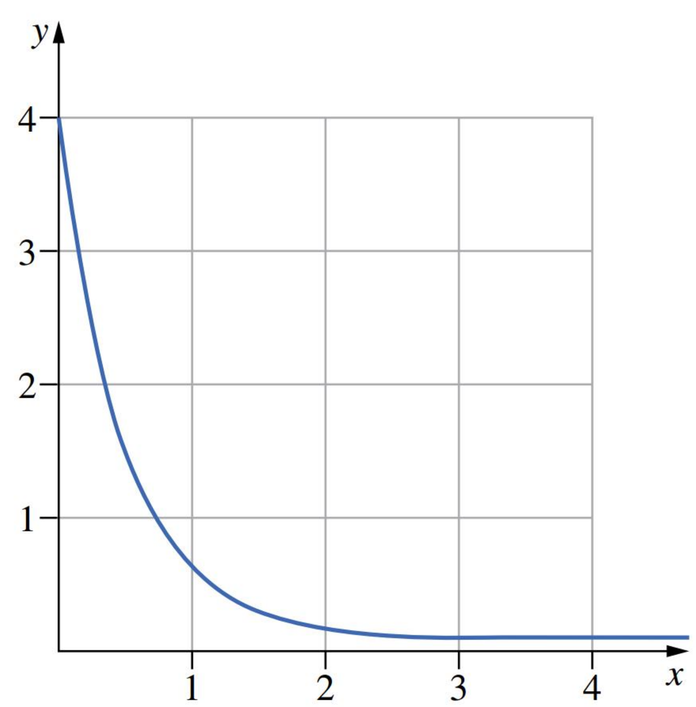


FIGURE 1.6.10 An exponential curve. In this example the equation of the curve is $y = 4e^{-x}$, indicating that the initial value of the graph is 4.

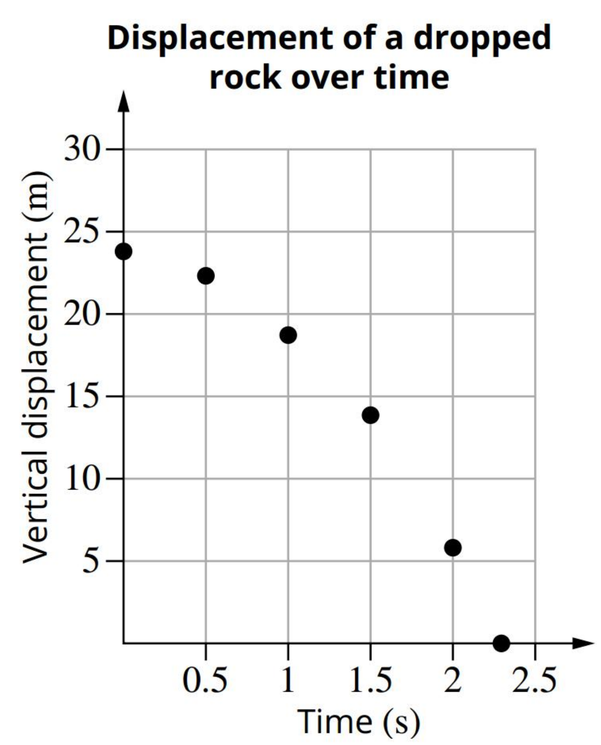


FIGURE 1.6.11 The square root curve. In this example the equation of the curve is $y = k\sqrt{x}$.

Table 1.6.1 summarises the common graphs seen in physics.

TABLE 1.6.1 A summary of the features of commonly encountered graphs and relationships used in physics

Graph type	Basic equation	How y changes with x	Rate of change of y
directly proportional	$y = mx$	increasing if $m > 0$ decreasing if $m < 0$	constant
linear	$y = mx + c$	increasing if $m > 0$ decreasing if $m < 0$	constant
parabolic	$y = kx^2$	increasing if $k > 0$, decreasing if $k < 0$	increasing
hyperbolic	$y = \frac{k}{x}$	decreasing	decreasing
periodic	$y = A \sin \omega x$ $y = A \cos \omega x$	oscillating between maximum and minimum	N/A
exponential decay	$y = Ae^{-kx}$	decreasing	decreasing
square root	$y = k\sqrt{x}$	increasing	decreasing

Outliers

Sometimes when you collect data, there may be one point that does not fit the trend and may be an error. This is called an **outlier**. An outlier is often caused by a mistake made in measuring or recording data, or from a random error in the measuring equipment. If you have an outlier in your results, you can include it in your graph but ignore it when drawing the line of best fit as in Figure 1.6.12.

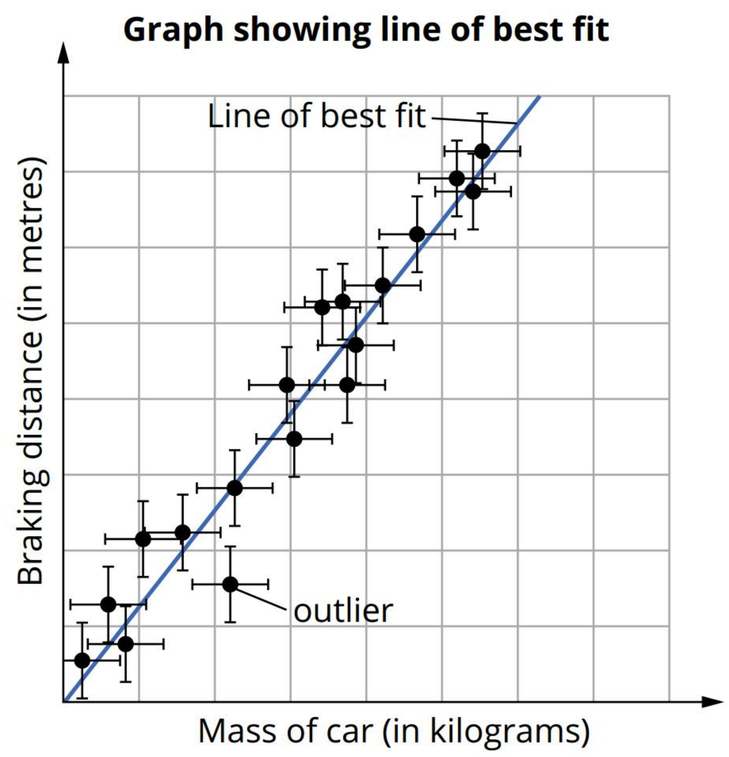


FIGURE 1.6.12 A scatter plot shows an outlier, which has been ignored when adding the line of best fit.

Distorting the truth

Poorly constructed graphs can distort the truth. For example, in Figure 1.6.13, you can see two graphs that show the same data—the test results of two groups of students. One group of students did not eat breakfast before doing the test and scored an average of 42 marks out of 50. The other group of students did eat breakfast and scored an average of 48 marks out of 50. One graph distorts the difference in marks between the two groups by using a scale of only 40 to 50 marks on the y-axis. It is important to make sure the graphs you create do not distort your data. You should also be wary of distorted data when interpreting graphs in other publications.

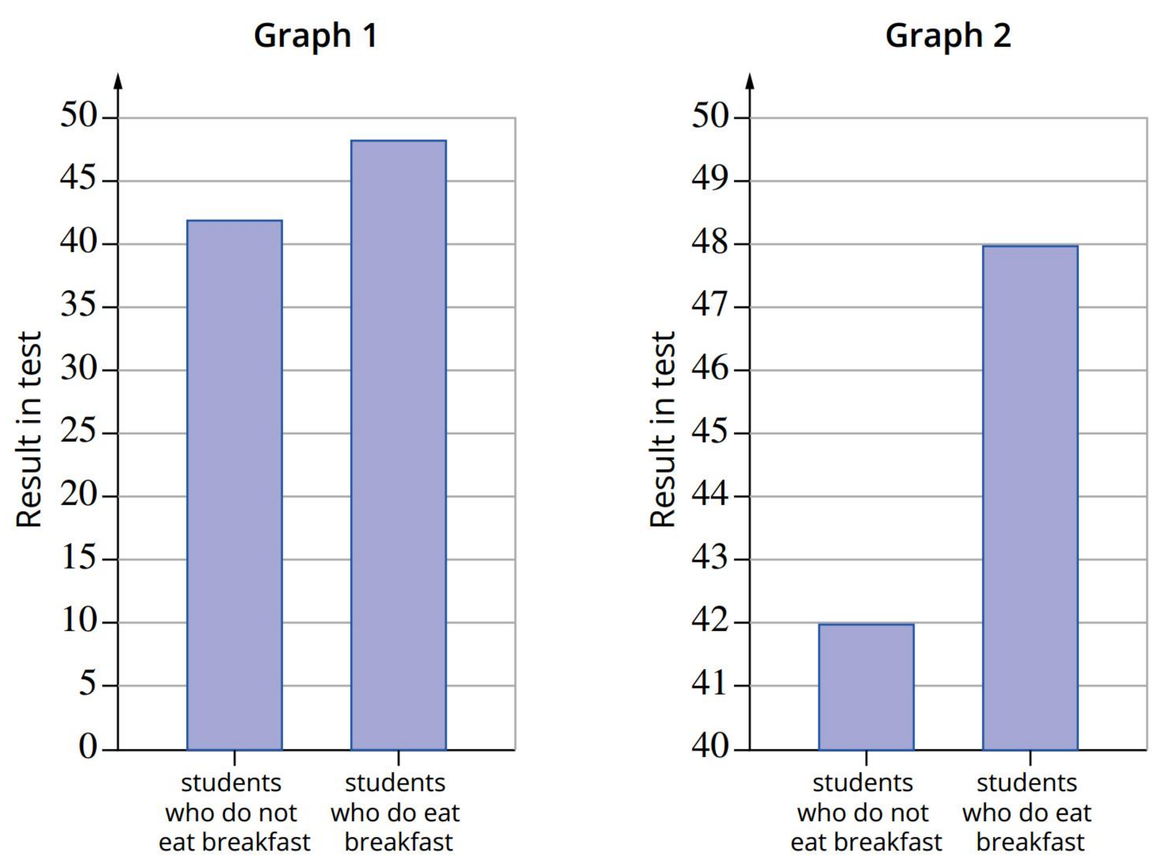


FIGURE 1.6.13 Graph 1 shows the difference between two groups of students out of the total 50 marks on the y-axis. Graph 2 shows the difference between the two groups within only a narrow range of marks on the y-axis, which distorts the difference and makes it appear larger than it really is.

1.6 Review

SUMMARY

- Tables and graphs are used to represent scientific data.
- In general, tables provide more detailed data than graphs, but it is easier to observe trends and patterns in data in graph form than in table form.
- Tables organise data into rows and columns, and can vary in complexity according to the nature of your data.
- Tables should have the following features:
  - a descriptive title
  - column headings (including the units and absolute uncertainty)
  - aligned figures (align the decimal points)
  - the independent variable placed in the left column
  - trials of the dependent variable placed subsequent columns
  - a column for the average
  - a column for uncertainty
- Graphs are used to display relationships, trends and patterns between two variables with one proposed to be dependent on the other.
  - Scatterplots are commonly used to display data in the form of a graph, and can be used for both raw and processed data.
  - Error bars indicate the absolute uncertainties in the independent and dependent values.
  - A trend line (line of best fit) is used to show the overall trend in the data, and can be used to predict values between the data points.
- An outlier is a data point that does not fit the trend, and may be caused by an error.

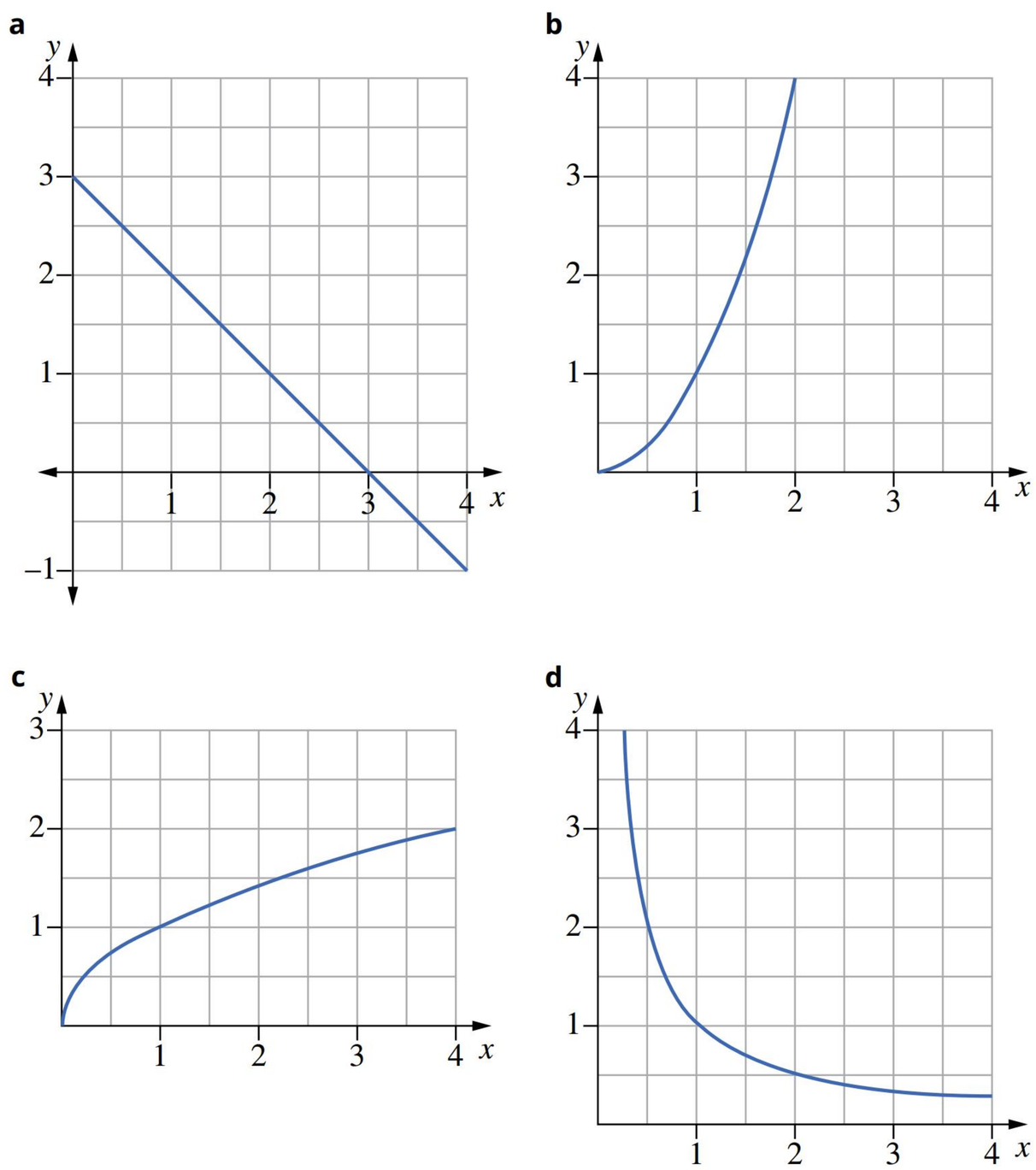
KEY QUESTIONS

Describe

1 State the purpose of a trend line.

2 Recall how systematic errors are shown on a graph.

3 Identify the type of relationship between the *x*- and *y*-variables that is shown in the following graphs.



Apply

4 Explain what outliers are.

5 Identify the relationship between the variables indicated by a linear graph that passes through the origin.

6 Identify the relationship that exists if one variable decreases as the other increases.

7 Describe the relationship that exists if both variables increase or both decrease at the same rate.

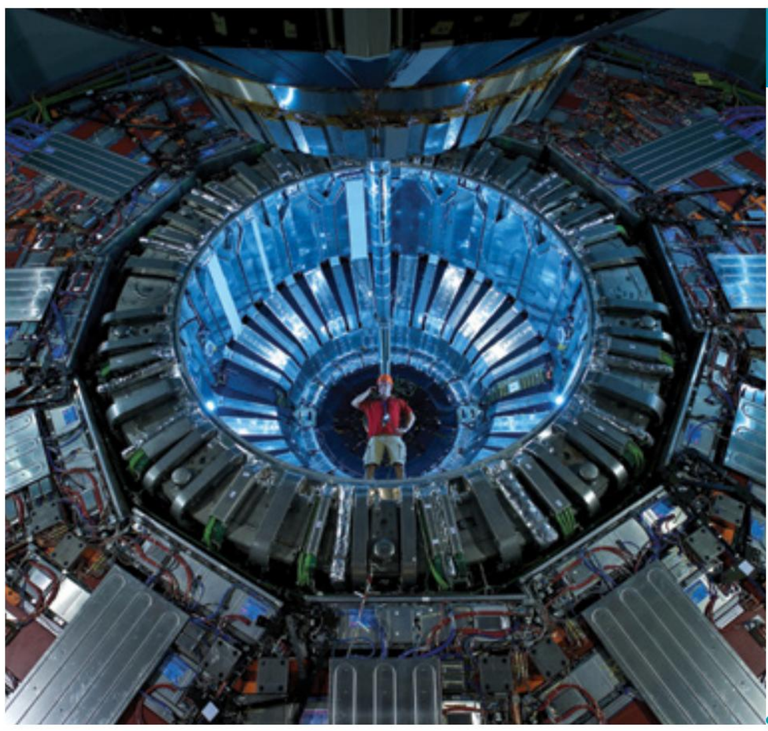
Analyse

8 If theory suggests that the *y*-intercept of a line is zero, deduce what this should look like on a linear graph.

9 Consider the data below and determine the relationship between atmospheric pressure and altitude.

Pressure (atm)	1.00	0.79	0.52	0.23	0.11	4.5×10^{-2}	1.3×10^{-2}	6.0×10^{-3}	2.1×10^{-3}
Altitude (km)	0	2.0	5.0	10.0	15.0	20.0	30.0	40.0	50.0

1.7 Data analysis



BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- calculate and interpret the range, mean, median and mode of a set of data
- display data, including error bars, line of best fit, minimum and maximum lines of primary and secondary data
- use the R^2 values to evaluate the fit of a trend to a set of data.
- linearise data that is not already producing a straight line graph
- use the equation of a straight line of best fit to determine the gradient and *y*-intercept
- use the minimum and maximum lines to calculate an uncertainty in the gradient and *y*-intercept
- use the gradient and *y*-intercept in further processing of data.

One of the difficulties in physics is that direct measurements of phenomena or measurements within a closed system are challenging to obtain. Therefore, the limitations and uncertainty in the data include uncertainties in the accuracy and precision of the measurements that were recorded as well as errors related to reliability and validity of the experimental procedure. To address this problem, physicists perform statistical analysis to help understand the quality of the measurements, the results and their meaning.

This module will outline a basic understanding of common statistical analysis used in physics relevant to the Physics General Senior Syllabus.

STATISTICAL MEASURES

There are several common statistical measures that help describe data accurately.

Range

The range is the difference between the highest and lowest values in a data set. Table 1.7.1 shows the measurements taken for two substances to come to thermal equilibrium.

TABLE 1.7.1 Time to reach thermal equilibrium for an aluminium block and 200 mL water initially at 20°C and 50°C

Temperature (°C)	t_1 (s)	t_2 (s)	t_3 (s)	t_4 (s)	t_5 (s)	Mean	Range
20	253	158	201	169	187	194	253 – 158 = 95
50	69	85	70	91	75	78	91 – 69 = 22

To determine the range for values in Table 1.7.1, you would subtract the smallest value from the largest value. Notice how an abnormally large or abnormally small value in the data set makes the variability appear high. If one value appears way out of range, such as the time taken to reach thermal equilibrium the first time the experiment was performed at 20°C, it may be an outlier. This illustrates the importance of observation during experiments and recording all details in a journal as experimentation and research is conducted.

The experiment was conducted with a smaller number of measurements taken at each temperature, and the results seen in Table 1.7.2.

TABLE 1.7.2 Time to reach thermal equilibrium for an aluminium block and 200 mL water initially at 20°C and 50°C

Temperature (°C)	t_1 (s)	t_2 (s)	t_3 (s)	Mean	Range
20	253	158	201	204	253 – 158 = 95
50	69	85	70	75	85 – 69 = 16

Even though the range has not changed much between Tables 1.7.1 and 1.7.2, the results at 20°C seem more random. In Table 1.7.2 at 50°C, the second reaction could be an outlier as the other two results show excellent agreement. The range simply outlines the total variation in measured results; no other analysis or interpretation can be achieved.

A larger **sample size** will strengthen the **validity** of the range

Measures of central tendency

Measures of central tendency (also called central location) are single values that allow you to describe the central position in a set of data. The mean, median and mode are all measures of central tendency. In Physics, the mean is most common. When a data table includes an 'average' column, the measure of central tendency being used will be the mean.

Consider the following data set: 3, 5, 7, 8, 8, 8, 10.

- The **mean** (or average) is the sum of the values divided by the number of values, which in this case is (3 + 5 + 7 + 8 + 8 + 8 + 10) ÷ 7 = 7.

$$\text{mean} = \frac{\Sigma(x_1 + x_2 + x_3 + \ldots)}{n}$$

where

Σ = sum of

$x_1 + x_2 + x_3 = \text{measurement}_1 + \text{measurement}_2 + \text{measurement}_3$

n = total number of measurements

- The **median** is the 'middle' value in an ordered list of values, which in this case is the fourth value, which is 8.
- The **mode** is the value that occurs most often in a list of values, which in this case is 8. This measure is particularly useful for describing qualitative or discrete data.

The appropriate measure of central tendency to use depends on the type of data you are working with (Table 1.7.3).

TABLE 1.7.3 When to use the different measures of central tendency

Type of data	Mean	Median	Mode
nominal (qualitative)	✗	✗	✓
ordinal (qualitative)	✗	✓	✓
discrete or continuous (quantitative)	✓	✓	✓

Graphically representing the data using central tendency provides a clear and succinct display of results. As there are many measured values and results in raw data, it can be difficult to analyse and interpret. It is much easier and less complicated to analyse and interpret processed data compared to raw data. Raw data includes all the measured results and usually a large number of measurements or observations.

Processed evidence is usually a smaller number of results that represent all the measured raw data; these representative results are calculated using statistical methods such as mean, median and mode. Therefore, an analysis can be conducted to compare results using three results (e.g. three means) rather than nine results (e.g. nine individual measurements in the raw data). Interpreting a relationship is also much easier and less complicated when using fewer numbers.

It is important to realise that statistical calculations do not produce the true value, but rather a single value (or smaller number of values) that is meant to represent many.

REGRESSION

Regression is the term used to state that the independent variable causes the result in the dependent variable during a scientific investigation. Some relationships between variables are causal, meaning that there is a cause-and-effect relationship. The independent variable is the cause, and the change dependent variable is the effect.

There are numerous statistical calculations that estimate the causal relationship between variables; some calculations provide a value that indicates how directly an independent variable causes the dependent variable result. This attempts to show the strength of the relationship, and to identify if the change in the dependent variable is entirely due to the independent variable.

In physics, not all relationships are direct or straightforward cause and effect. Often there are many variables that influence the dependent variable, and it is helpful to try and predict how much of an effect the independent has on the dependent, while other variables are also influential.

Coefficient of determination (R^2)

The **coefficient of determination** (R^2) can calculate a value that indicates the predictability between the variables based on how much the results vary. The coefficient of determination produces a value that is an estimate as to how well you can predict the dependent variable based on the independent variable, considering the variations in the results. In the examples in Figure 1.7.1, the data of technique 1 does not follow the linear trend line exactly and therefore as the concentration changes (the independent variable), the absorbance (dependent variable) does not always change consistently. Sometimes it changes by 5, sometimes by 2 or even by 10 or more. The coefficient of determination (R^2) is a calculation that considers the variation in the results to estimate the predictability.

For example, a group of students has used two different techniques of recording the time taken for an object to roll down inclined planes at different angles (Figure 1.7.1). Technique 1 used a stopwatch while technique 2 used light gates.

Based on the lines of best fit and R^2 values, the second technique was chosen to record the data for the experiment.

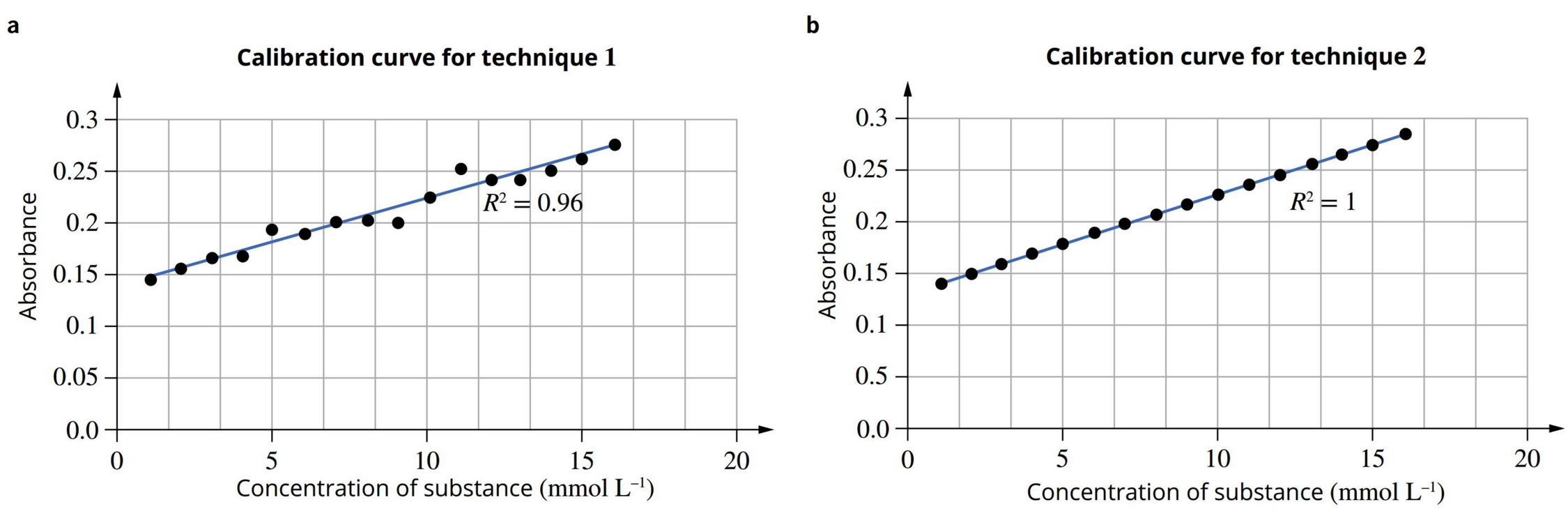


FIGURE 1.7.1 (a) Experimental data recorded with a stopwatch: linear regression was used to establish a line of best fit. (b) Experimental data recorded with light gates: linear regression was used to establish a line of best fit.

Even though both techniques measured the same experiment, the data is different. As can be seen in the graphs, the linear trend line is very similar with a similar slope; however, technique 1 has an R^2 value of 0.96 and technique 2 is 1.00.

The coefficient of determination produces a value between 0 and 1. If the value is 0, it is unable to predict the change in the dependent variable from the independent variable due to so much variation in the results. If the value is 1, then it can predict the change in the dependent variable 100% of the time without error. Any other number between 0 and 1 is considered a percentage, for example 0.76 means that the coefficient of determination can predict 76% of the dependent variable results due to the independent variable. It is interpreted as 76% of the variation in the dependent variable can be explained by the independent variable.

In Figure 1.7.1b, the time is perfectly correlated to the angle without error. This suggests that the results from this method, including error, **bias** and instrumental precision, are highly reliable.

Figure 1.7.1a shows that the time was not precisely correlated with angle. The R^2 value for this method is slightly lower meaning the results are less predictable due to more variation. This method is less precise compared therefore the use of light gates was the preferred technique to collect experimental data in this case.

LINEARISING DATA

A linear relationship is easy to analyse when processing raw data. The y-intercept and constant gradient are both readily calculated, and the values often represent physical quantities. For example, the gradient of a graph of force against acceleration gives us the mass of the object from $F = ma$.

So, what happens if your raw data graph is *not* a straight line?

There are ways of processing the curved raw data to obtain values of constants, but they are not easy. A way around this is to convert the raw data into straight-line data via a process called linearisation.

Linearisation involves changing what is graphed along the horizontal and/or vertical axes so that a linear graph is produced. Note that this process does not alter the raw data in any way; it just changes how it is displayed as a graph and is a legitimate way of processing data.

For example, in an experiment the vertical displacement of a dropped rock was measured at various times from an initial height of 24.0 m. The data is shown below in Table 1.7.4 and is used to find a value for the acceleration due to gravity, g. Note that uncertainties were recorded but have been removed for this first example.

TABLE 1.7.4 Raw data of the height above the ground of a dropped rock at various times

Time (s)	Height above ground or displacement (m)
0.0	24.0
0.5	22.5
1.0	18.9
1.5	13.9
2.0	5.9
2.3	0.0

A graph of the raw data, with time on the x-axis and displacement on the y-axis, shows a parabolic relationship (Figure 1.7.2).

As this graph is not linear, it is not immediately apparent how to obtain information about the acceleration due to Earth's gravity. To analyse this data, the graph needs to be linearised to produce a straight line. The data 'looks' parabolic and this is backed up by the quadratic equation that relates the vertical displacement, s, of a falling object under Earth's gravity, g, over time, t.

Linear graphs are the easiest to analyse in physics as they have a y-intercept and a constant gradient.

If raw data does not show a linear trend, the data can be linearised. This involves modification of what is displayed along the independent and dependent axes to show a linear trend.

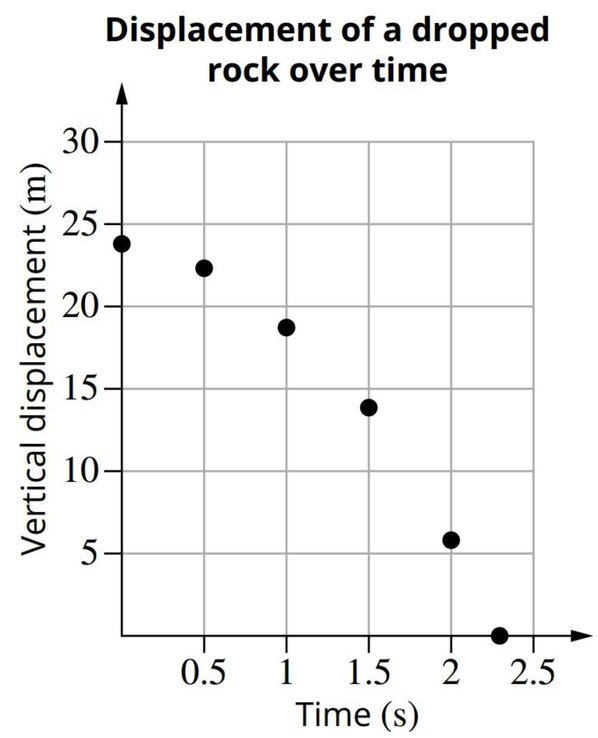


FIGURE 1.7.2 The graph shows a parabolic relationship between vertical displacement of an object falling under Earth's gravity and time.

This is a parabolic relationship between s and t because the independent variable, t, is squared.

To linearise this equation, you transform it into the straight-line equation $y = mx + c$, as shown in Figure 1.7.3. You then match the variables s to y and t^2 to x (shown in blue). You can see the gradient and y-intercept of the linearised t^2 graph (shown in red).

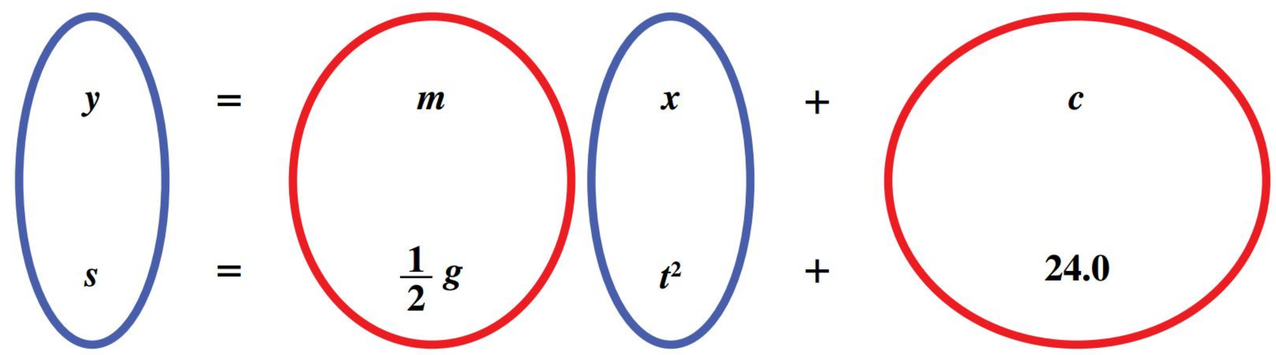


FIGURE 1.7.3 Linearising an equation

To linearise the quadratic equation $s = \frac{1}{2}gt^2 + 24.0$, you equate it to the general equation of a straight line $y = mx + c$:

s is plotted on the y-axis.

t^2 is plotted on the x-axis.

The gradient is $m = \frac{1}{2}g$.

The y-intercept is $c = 24.0$.

For the linearised version of the data, s is still on the y-axis, but the x-axis will now be t^2 rather than t. Time is squared, so insert a new column in the table of data. The y-intercept is the displacement when t is zero. From the table you can see that y-intercept is 24.0 m.

Note that in Table 1.7.5, the time^2 column is inserted immediately to the right of the original time data and that the unit of time is also squared. No change has been made to the displacement column.

TABLE 1.7.5 Processed data including time^2 to be used for the linearised version of the relationship between displacement and time

Time (s)	Time^2 (s^2)	Height above ground or displacement (m)
0.0	0.00	24.0
0.5	0.25	22.5
1.0	1.00	18.9
1.5	2.25	13.9
2.0	4.00	5.9
2.3	5.29	0.0

A graph of displacement versus time^2 should now be a straight line. Figure 1.7.4 shows this as a very good linear fit to the data (R^2 of 0.9994). The linear trend line is also shown.

From the trend line, the gradient is $-4.4744\,\mathrm{m\,s^{-2}}$, and y-intercept is 23.738 m.

The y-intercept value of 23.738 m is close to the actual y-intercept of 24.0 m, so it is an accurate result.

The gradient value of $-4.744\,\mathrm{m\,s^{-2}}$ is much lower than the expected value of the acceleration due to Earth's gravity, g, which is $-9.80\,\mathrm{m\,s^{-2}}$, so what went wrong? Remember (from Figure 1.7.4) that:

$$\text{gradient} = \frac{1}{2}g$$

$$\therefore\ g = \text{gradient} \times 2$$

$$g = -4.4744 \times 2$$

$$= -8.9488\,\mathrm{m\,s^{-2}}$$

This value is still slightly inaccurate but that is probably due to air resistance encountered by the falling rock.

This example showed that from non-linear raw data, a linear trend line could be used to find the values of the gradient and y-intercept.

Note that you can only linearise data if there is a relationship between the x- and y-variables in the first place, otherwise the linearisation process is meaningless. Figure 1.7.5 shows that linearisation is not possible if there is no relationship between the variables.

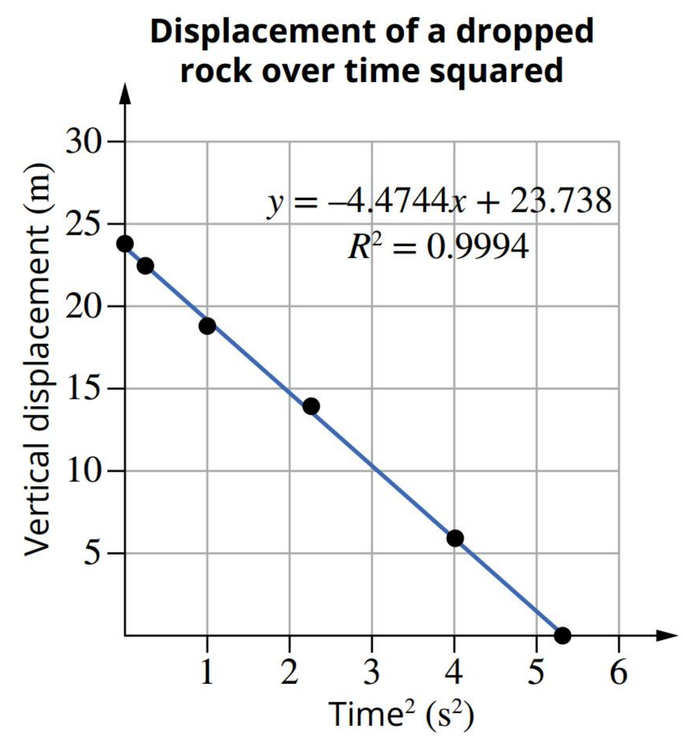


FIGURE 1.7.4 The linearised graph of vertical displacement against time^2, allowing the gradient and y-intercept to be used to calculate the acceleration due to Earth's gravity.

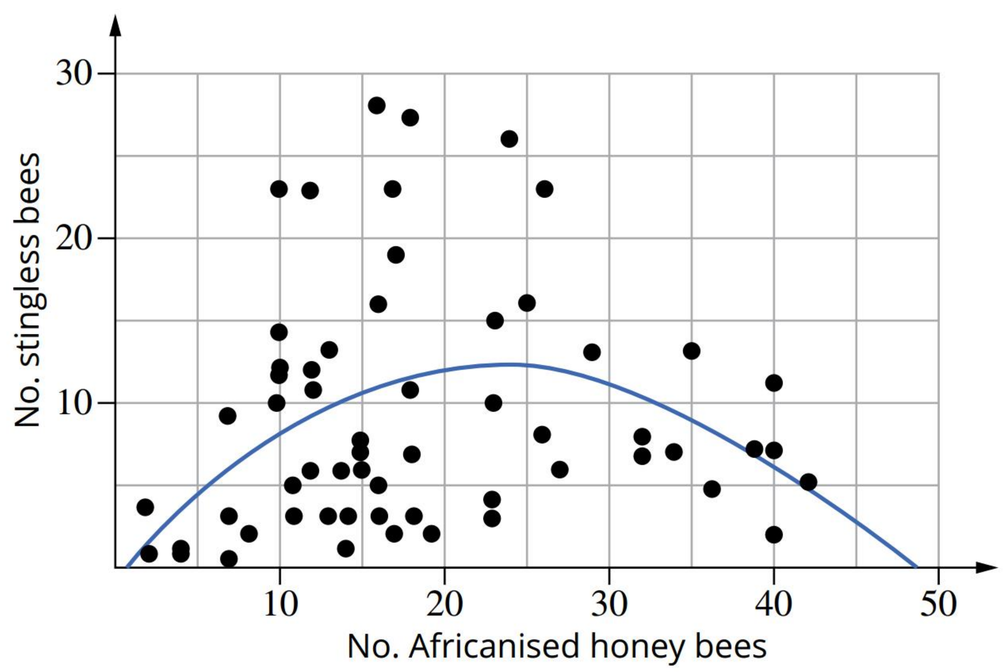


FIGURE 1.7.5 An extremely poor best fit line to the data that was published in the journal *Science* in 1978.

Sometimes the relationship between the x- and y-variables is known, but often it is unknown. This is what makes data analysis in physics exciting: using data and uncertainties to find an otherwise hidden relationship between the dependent and independent variables.

Worked example 1.7.1

LINEARISING DATA

Below are two formulas used in physics. Descriptions of the shapes of the graphs when the raw data is graphed are given in brackets. Assume that all other symbols are constant. For each formula:

i state the variable that would need to be graphed on each of the horizontal and vertical axes of a graph to linearise these equations

ii state the values of the gradient and y-intercept.

a $E_k = \frac{m}{2}v^2$ (E_k on the y-axis and v on the x-axis produce a parabola.)

Thinking	Working
i v is on the x-axis and the graph is a parabola, so the new x-axis variable will be v^2. The y-axis variable, E_k, will not be modified.	New x-axis variable = v^2 New y-axis variable = E_k (unchanged)
ii $E_k = \frac{1}{2}mv^2 + 0$ The y-intercept is zero. The coefficient of v^2 is $\frac{m}{2}$.	y-intercept = 0 gradient = $\frac{m}{2}$
b $F = \frac{GmM}{r^2}$ (F on the y-axis and r on the x-axis produce a hyperbola.)	
Thinking	**Working**
i r is on the x-axis and the graph is a hyperbola, so the new x-axis variable will be $\frac{1}{r^2}$. The y-axis variable, F, will not be modified. Note that technically a hyperbola is proportional to $\frac{1}{r}$, but the general shape and linearisation process is the same for $\frac{1}{r^2}$, $\frac{1}{r^3}$, etc.	New x-axis variable = $\frac{1}{r^2}$ New y-axis variable = F (unchanged)
ii $F = GmM\left(\frac{1}{r^2}\right) + 0$ The y-intercept is zero. The coefficient of $\frac{1}{r^2}$ is GmM.	y-intercept = 0 gradient = GmM

➤ Try yourself 1.7.1

LINEARISING DATA

Below are two formulas used in physics. Descriptions of the shapes of the graphs of the raw data are given in brackets. Assume that all other symbols are constant.

i State the variable that would need to be graphed on each of the horizontal and vertical axes of a graph to linearise these equations.

ii For each formula, state the values of the gradient and y-intercept.

a $T = 2\pi\sqrt{\frac{L}{g}}$ (T on the y-axis and L on the x-axis produce a square root graph.)

b $\frac{1}{d_j} = \frac{1}{f} - \frac{1}{d_o}$ (d_i on the y-axis and d_o on the x-axis produce a hyperbola.)

Table 1.7.6 summarises the commonly encountered relationships in physics and shows how to linearise each equation. Note that you will not be expected to linearise periodic relationships.

TABLE 1.7.6 A summary of common relationships in physics, and how to linearise the raw data to produce a straight line. Note that for parabolic, inverse and square root relationships there is more than one way to linearise the raw data.

Graph type	Basic equation	New *x*-axis	New *y*-axis	New gradient
directly proportional	$y = mx$	already linear	already linear	no change
linear	$y = mx + c$	already linear	already linear	no change
parabolic	$y = kx^2$	x^2	no change	k
		x	$\sqrt{y}$	$\sqrt{k}$
inverse (hyperbolic)	$y = \frac{k}{x}$	$\frac{1}{x}$	no change	k
		x	$\frac{1}{y}$	$\frac{1}{k}$
inverse square	$y = \frac{k}{x^2}$	$\frac{1}{x^2}$	no change	k
		x^2	$\frac{1}{y}$	$\frac{1}{k}$
exponential	$y = A\,e^{-kx}$	x	$\ln y$	$-k$
square root	$y = k\sqrt{x}$	$\sqrt{x}$	no change	k
		x	y^2	k^2

THREE-LINE GRAPHS

Any graph showing the relationship between two variables should also include uncertainties as error bars. When raw or processed data yields a straight line, the uncertainties can be used to determine the uncertainty in the gradient and *y*-intercept of the line of best fit. This is done via the use of the lines of maximum gradient and minimum gradient in addition to the line of best fit.

- The maximum gradient line is found by lining up a straight line such that it passes through all of the error boxes (at least part of either the error bars for *y* or *x* of every data point) at the steepest possible gradient.
- The minimum gradient line is found by lining up a straight line such that it passes through all of the error boxes at the shallowest possible gradient.

Note that this can be tedious to do by hand and software is available that will do this automatically.

Figure 1.7.6 shows an example of a linear graph, the best fit trend line and the maximum and minimum lines.

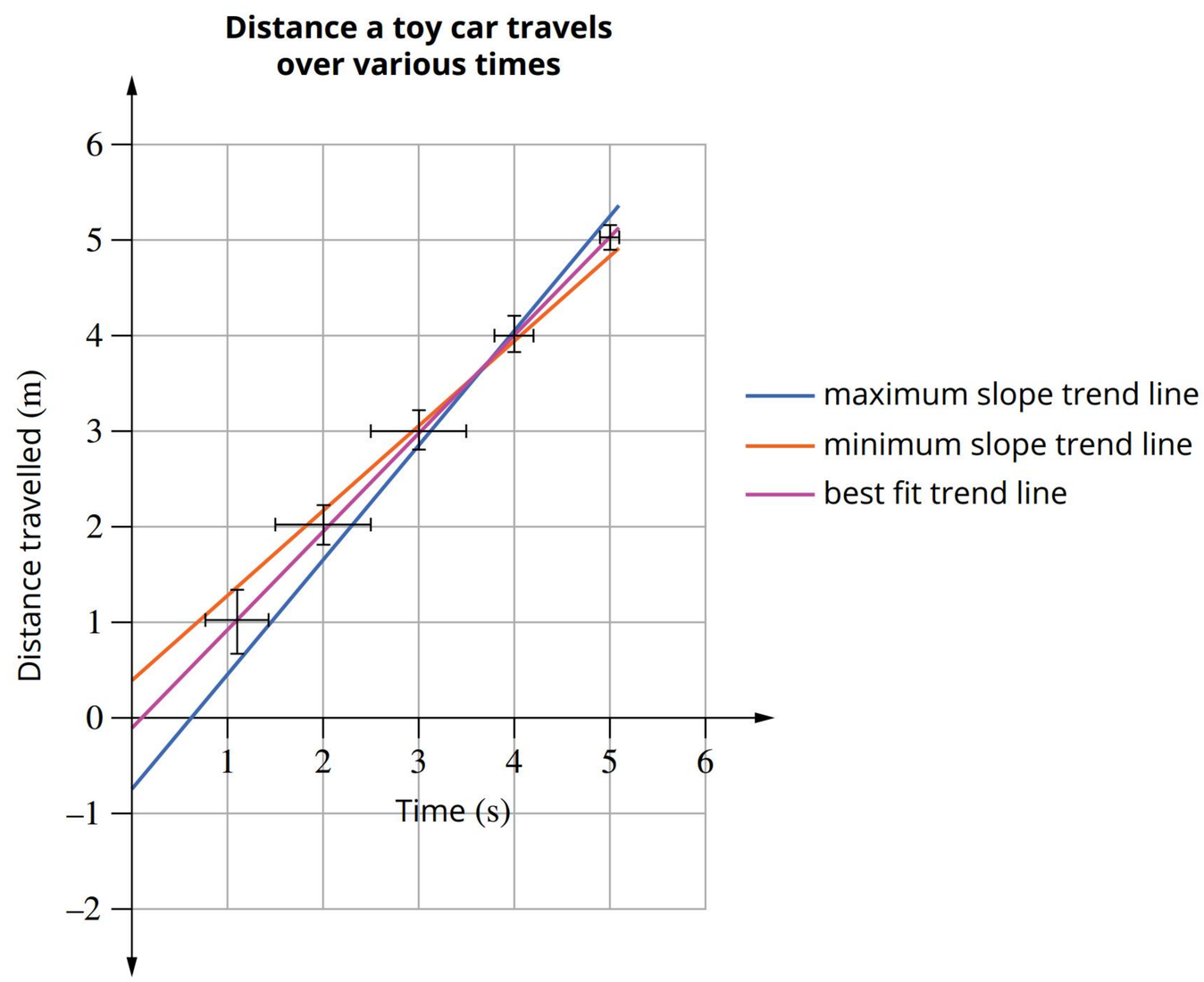


FIGURE 1.7.6 An example of a linear graph showing the best fit line, error bars, and maximum and minimum lines. The minimum and maximum lines are used to determine the uncertainty in the gradient and *y*-intercept.

If calculations are to be done manually, determine the values of the three slopes (line of best fit, maximum line and minimum line) by choosing two points on each line, not the data points. The *y*-intercept of each of the three lines can be read off the *y*-axis. Remember to also include units in your calculations.

If the gradient and *y*-intercepts are done automatically, they can be read off from the equations of the lines generated by the software. In Figure 1.7.6, the three equations are:

line of best fit: $y = 1.02x - 0.0803$

maximum line: $y = 1.19x - 0.753$

minimum line: $y = 0.881x + 0.407$

These data tell us that the difference between the maximum and minimum gradients, and maximum and minimum *y*-intercepts, are not very large, so the data is quite precise. The line of best fit also lies between the maximum and minimum lines.

The uncertainty of the gradient can be found by using:

$$\Delta\text{gradient} = \frac{\text{maximum gradient} - \text{minimum gradient}}{2}$$

And, similarly, the uncertainty in the *y*-intercept can be found using:

$$\Delta(y\text{-intercept}) = \frac{\text{maximum } y\text{-intercept} - \text{minimum } y\text{-intercept}}{2}$$

Maximum and minimum gradient lines show the uncertainty in the gradient and *y*-intercept in linear data.

Using the data from Figure 1.7.6, the uncertainties of the gradient and y-intercept are:

$$\Delta\text{gradient} = \frac{1.19 - 0.881}{2}$$
$$= 0.1545\,\text{m s}^{-1}$$
$$= 0.15\,\text{m s}^{-1}$$

$$\Delta(y\text{-intercept}) = \frac{0.407 + 0.753}{2}$$
$$= 0.58\,\text{m}$$
$$= 0.6\,\text{m}$$

Finally, using the correct significant figures and decimal places of uncertainties, the final values of the gradient and y-intercept are:

gradient = $1.02 \pm 0.15\,\text{m s}^{-1}$

y-intercept = $-0.08 \pm 0.6\,\text{m}$.

Note that in this example:

- the gradient represents speed (Distance traveled/time = m/s). The toy car is travelling at a constant speed of $1.02 \pm 0.15\,\text{m s}^{-1}$.
- the y-intercept represents the initial distance travelled. This is expected to be zero, because at time zero the toy car is at the start. The value of the y-intercept has a range of values from +0.5 m to −0.7 m, which includes the expected 0 m. This indicates that the data is quite accurate for this variable.

Table 1.7.7 shows data from an experiment in which the masses and volumes of solid copper cubes were measured in order to find the density of copper (with uncertainty).

TABLE 1.7.7 Raw data of the masses and volumes of five different solid copper cubes that will be graphed and used to determine the density of copper and its uncertainty

Volume of copper cube (±5 mL)	Mass of copper cube (±10 g)
1	10
8	70
24	220
53	480
125	1120

This data is now graphed with volume on the x-axis and mass on the y-axis. Each error bar is shown, but the y-axis error bars are very small and difficult to see. Figure 1.7.7 shows the line of best fit as the purple dotted line, with the orange and blue dotted lines being the maximum and minimum lines respectively. The equations of each line is also shown, along with the R^2 value for the line of best fit.

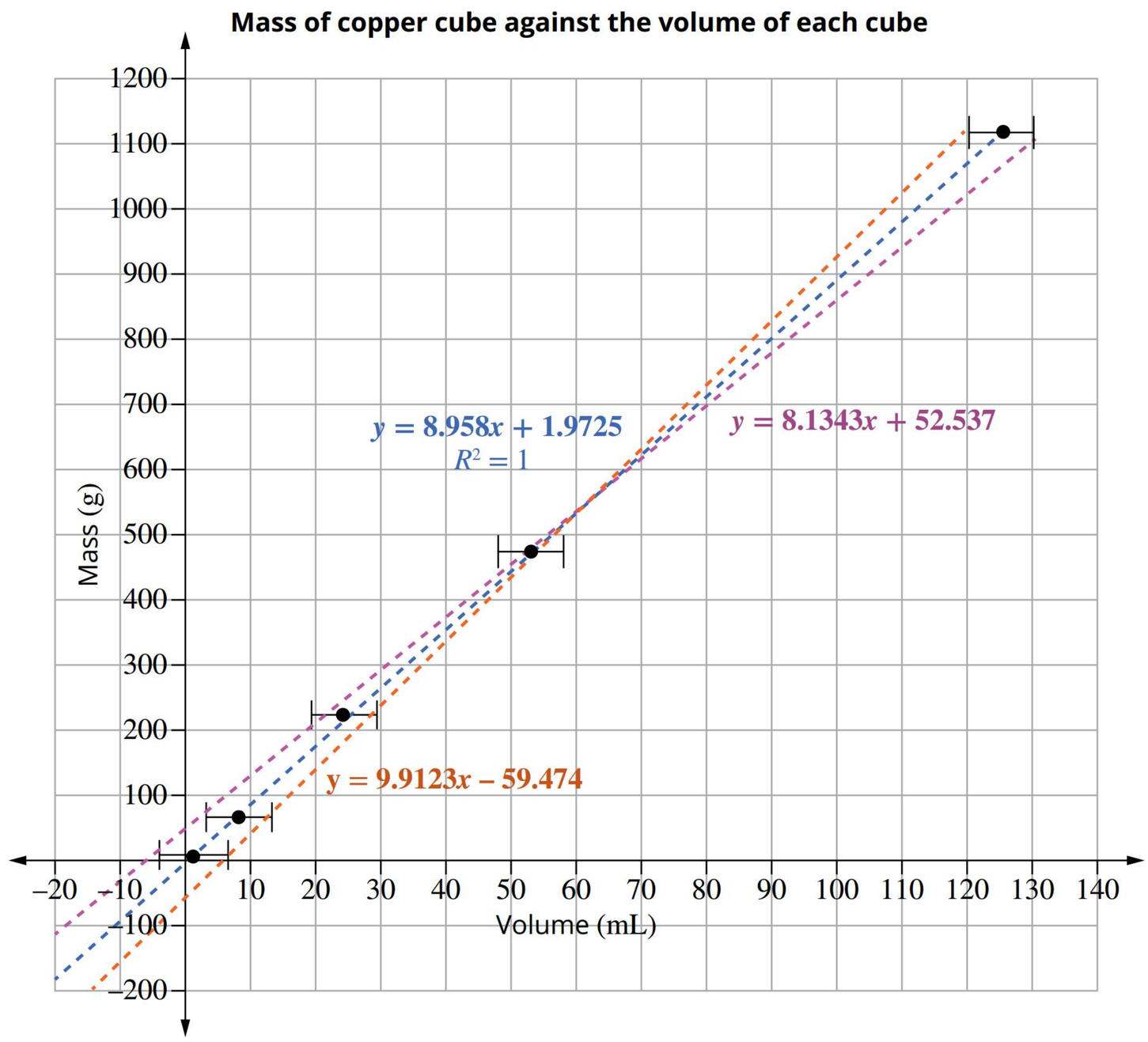


FIGURE 1.7.7 The complete graph, error bars and maximum and minimum lines for mass and volume data of copper cubes, the dots at the extremities of the lines were used to help draw the maximum and minimum lines.

From the line of best fit (red):

gradient = $8.958\,\text{g mL}^{-1}$
y-intercept = $1.9725\,\text{g}$.

From the graph:

$$\Delta\text{gradient} = \frac{9.9123 - 8.1343}{2} = 0.889\,\text{g mL}^{-1} = \pm 0.9\,\text{g mL}^{-1}$$

$$\Delta(y\text{-intercept}) = \frac{52.537 - (-59.474)}{2} = 56.006\,\text{g} = \pm 60\,\text{g}$$

Note that in this example:

- the gradient represents the density of copper (mass/volume = g/mL), which is $9.0 \pm 0.9\,\text{g mL}^{-1}$. This is a reasonably precise measurement with a 10% uncertainty, and the discrepancy between this value and the accepted value ($\tilde{n}_{\text{copper}} = 8.96\,\text{g mL}^{-1}$) is only 0.4%.
- the y-intercept represents the mass of a copper cube with zero volume, which is $2 \pm 60\,\text{g}$. You would expect this to be zero because any solid with no volume has no mass. The value of the y-intercept ($2 \pm 60\,\text{g}$) contains the expected value of zero in its range from $-58\,\text{g}$ to $62\,\text{g}$.

The trend line passes through every error bar, so the data is free of outliers and matches theory. The precision of the data can be increased by using a higher resolution balance and callipers to reduce the uncertainty in mass and volume, although it was the uncertainty in volume that was the main source of uncertainty in the calculations. There is no evidence of systematic error because the value of the y-intercept contains the expected value of zero in its range.

Systematic and random errors in graphs

Graphs can reveal systematic and random uncertainties. Systematic errors will reveal themselves on linear graphs if the actual measurements do not match the predicted values, but there is an obvious pattern. Random uncertainties show as error bars, and these can be used to determine the uncertainty in the gradient and y-intercept of the line of best fit.

Incorrectly calibrated equipment will give the type of graph shown in Figure 1.7.8. This type of systematic error comes from an incorrectly scaled instrument.

For example, a ruler that has an incorrectly calibrated scale could read 1.2 cm when it should read 1.0 cm, and read 2.4 cm when it should read 2.0 cm.

Incorrectly zeroed equipment will give the type of graph shown in Figure 1.7.9. All measurements along the y-axis are offset by the same value.

For example, an electronic balance incorrectly zeroed could read 1.4 g when it should read 1.1 g, and 23.7 g when it should read 23.4 g.

Any graph showing the relationship between two variables should also include uncertainties as error bars. When raw or processed data yields a straight line, the uncertainties can be used to determine the uncertainty in the gradient and y-intercept of the line of best fit. This is done via the use of the lines of maximum gradient and minimum gradient as explained earlier in this module.

Systematic errors are seen in graphs when every data point is shifted out of its theoretical position by the same amount or same ratio.

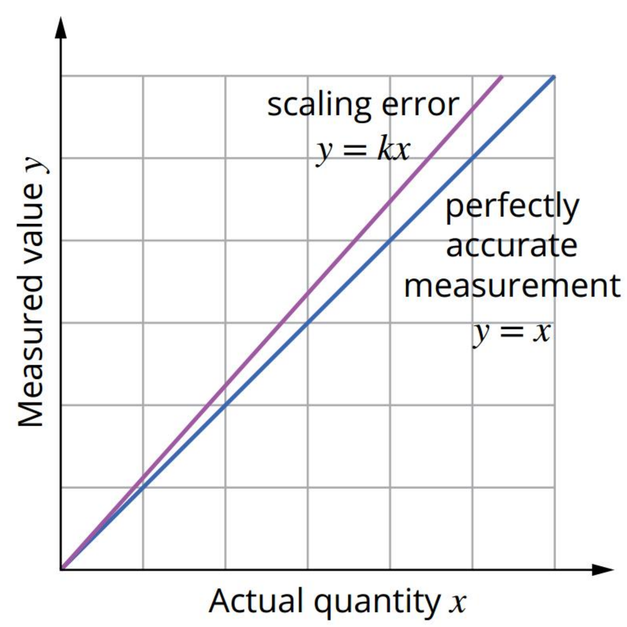


FIGURE 1.7.8 The recorded measurements are k times their real values. This means that the instrument's scale did not match the scale indicated on the display or on the graduated marks.

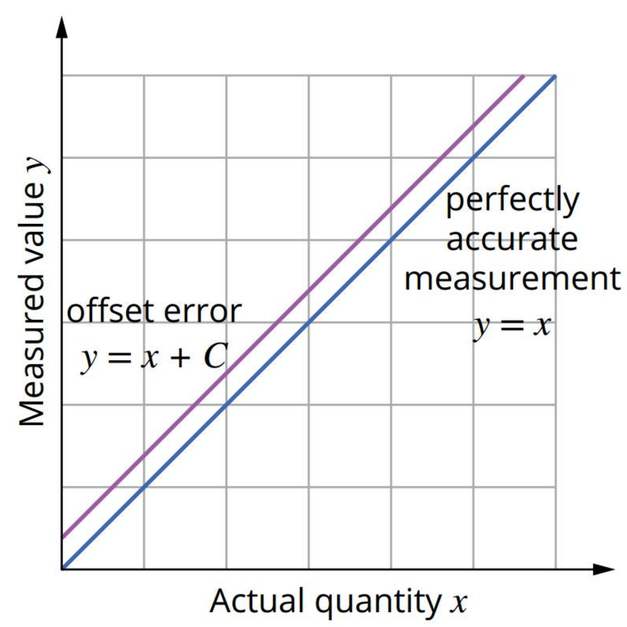


FIGURE 1.7.9 The recorded measurements need to be reduced by C to give the real values. This means that the instrument was not fully reset to zero before measurements were made.

1.7 Review

SUMMARY

- The mean, $\bar{x}$, is the average of a data set. It is calculated using the formula:
  $\bar{x} = \frac{\sum x_1 + x_2 + x_3 \ldots}{n}$, where
  Σ = sum of
  $x_1 + x_2 + x_3$ = measurement$_1$ + measurement$_2$ + measurement$_3$
  n = total number of measurements.
- The median is the 'middle' value in an ordered list of values.
- The mode is the value that occurs most often in a data set.
- Regression is the term used to state that the independent variable causes the result in the dependent variable during an experiment.
- Linear regression is a calculation that estimates a direct linear relationship between the independent and dependent variables.
- The coefficient of determination estimates how well you can predict the dependent variable based on the change in the independent variable.
- The coefficient of determination produces an R^2 value between 0 and 1.
  - The closer R^2 is to 0 the less predictable the dependent result is based on the independent value.
  - The closer the R^2 is to 1 the more predictable the dependent result is based on the independent value.
- Systematic errors appear in graphs where the data for x or y are shifted or multiplied by the same value.
- Commonly used graphs in physics are linear, parabolic (squared), inverse (hyperbolic), inverse square, sine and cosine, and exponential decay curves.
- A linear graph is the easiest to analyse because it is straightforward to calculate the gradient and y-intercept, and these are used in further processing of the data.
- Some graphs that are not linear can be linearised to produce a graph that has modified x- and y-axes.
- The minimum and maximum lines are used to calculate the uncertainty in the gradient and y-intercept.

KEY QUESTIONS

Describe

1 Describe the terms 'mean', 'median' and 'mode'.

2 Describe the coefficient of determination.

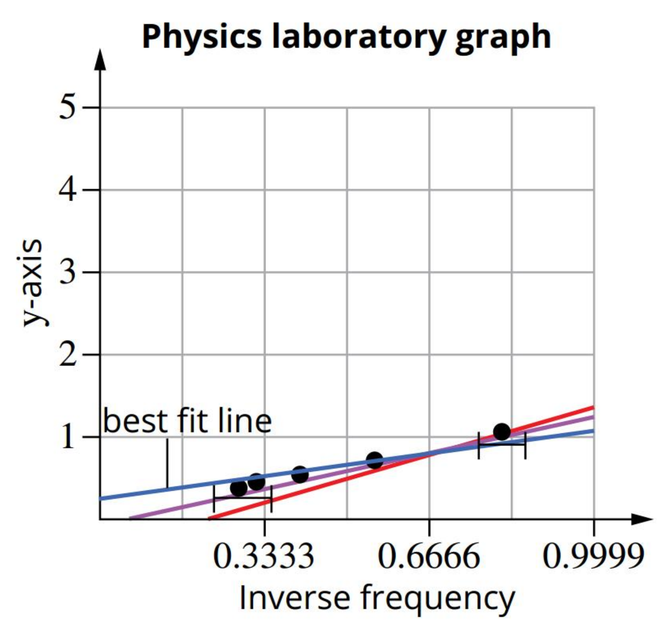
3 Explain why linear graphs are much easier to analyse than curved graphs, such as parabolic or hyperbolic graphs.

Apply

4 For the data set {21, 28, 19, 19, 25, 24, 20}, calculate the:

a range
b median
c mode
d mean
e standard deviation.

5 Consider the graph shown below.



a List the mistakes or poor techniques in this graph.
b For each mistake in your list, identify how the graph could be corrected or improved.

Analyse

6 Identify which of the statistical measurements of mean, mode and median is generally most affected by an outlier.

7 Melissa draws a straight line graph of data, including error bars, from an experiment she has just completed. She finds that it is not possible to draw a straight line of best fit through every error bar. Explain to Melissa why this is the case and suggest some improvements to her data.

8 If theory suggests that the *y*-intercept of a line is zero, deduce what this should look like on a scatter plot with a line of best fit.

9 Below are two formulas used in physics. A description of the shape of the graph of the raw data is given in brackets. Assume that all other variables are constant.

- **i** Describe what modified variables, if any, need to be plotted on each axis to produce a linear graph.
- **ii** Identify the gradient and *y*-intercept in each case.

a $F = \frac{kQq}{r^2}$ (F on the *y*-axis and r on the *x*-axis produces an inverse square graph)

b $B = \frac{\mu_0 I}{2\pi r}$ (B on the *y*-axis and I on the *x*-axis produces a straight line.)

10 The resistance, R, of an unknown, constant resistor can be found by using voltage, V, and current, I, data in a circuit. The theoretical relationship between voltage and current is given by $I \propto V$. The results of the experiment are recorded in the table.

Voltage $V \pm 0.5$ V	2.0	4.0	6.0	8.0	10.0
Current $I \pm 0.03$ A	0.19	0.44	0.55	0.68	0.94

a Identify the independent and dependent variables.

b Draw a graph of this data, using suitable axes, scales, labels and error bars.

c Draw the line of best fit.

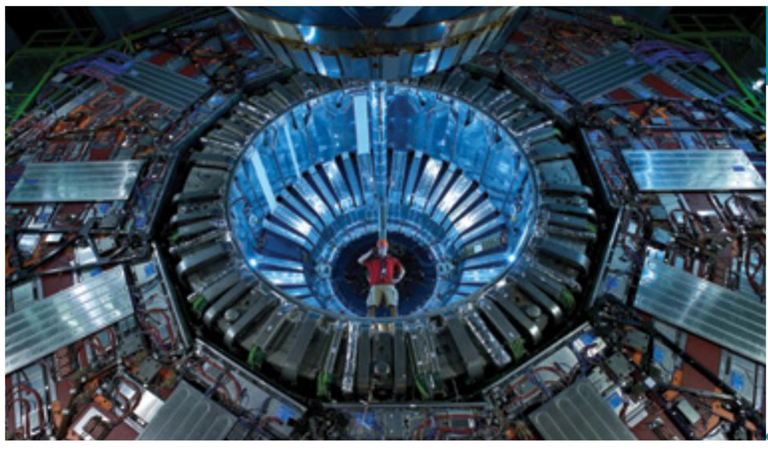
d Draw the maximum and minimum lines.

e Determine the gradient of the line of best fit, maximum line and minimum line.

f Calculate the value of the resistor and its uncertainty.

g Comment on the value of the *y*-intercept and its uncertainty.

1.8 Scientific writing



BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- use scientific language and representations
- use a scientific journal for experiments
- reference sources and avoid plagiarism
- use and reference AI in research and writing
- communicate findings in a multimodal presentation.

The QCAA requires you to complete a student experiment as part of Unit 3 Physics and a research investigation in Unit 4 Physics. Both tasks require written or multimodal presentations. Preparing and presenting scientific reports and investigations involves research and note-taking skills, use of scientific genre, language and representations, and referencing knowledge to acknowledge sources used.

Scientists follow strict genre conventions when undertaking and communicating their work. These are described in this module. Refer back to this module as you complete the Student experiment and Research investigation.

SCIENTIFIC WRITING AND REPRESENTATIONS

Scientific reports must be written using scientific language and representations; these should be relevant, fluent and concise. To meet the word count or time requirements, only use the words required to communicate your information, and avoid repetition. Having a plan and using a journal also helps to achieve fluent and concise writing. Use the syllabus objectives, specifications, and the instrument specific marking guide (ISMG) to plan an outline of each section of your written task.

Table 1.8.1 demonstrates communication of the same concept in a few different ways. Being fluent and concise will significantly help the word count of the report and the quality of the writing.

TABLE 1.8.1 Communicating concepts in various ways

Concept: the basic structure of an atom	
Communication	**Commentary of communication**
An atom is made up of protons, neutrons and electrons.	This is fluent and concise, but lacks scientific terms or language to convey in-depth understanding.
Atoms are tiny little objects made up of numerous parts that form the basis of matter. Atoms are made up of electrons, neutrons and protons. The electrons are found away from the centre of the atom. The centre of the atom contains the protons and neutrons.	This is fluent, but not concise. There is repetition (e.g. 'tiny' and 'little'—these terms have the same meaning; also 'made up' is stated twice). It also uses many words without using scientific terms to provide detail and understanding. This may be useful language in the journal when learning about a topic, but not in the scientific report.
Atoms are particles composed of three subatomic particles: the proton, electron and neutron. The centre of an atom is the nucleus and contains the protons and neutrons, with the electrons occupying space external to the nucleus.	This is fluent and concise. Repetition is avoided. Much in-depth understanding is communicated through scientific terms, which enable relevant information to be conveyed in fewer words.

Reports are written using paragraphs, with each paragraph explaining only one idea. The first sentence (topic sentence) of the paragraph introduces the topic. Following sentences provide the details of the idea. The final sentence concludes the idea and may also link to the idea of the next paragraph. Each sentence should flow onto the next, slowly building the details of the explanation. Headings and subheadings can be used to structure and break up the report.

Reports can be written in first person, active voice, or third person, passive voice (Table 1.8.2). First-person voice can be clearer, but it can put the focus on who is doing the action, whereas third-person voice focuses on the action itself.

Reports should be written using:

- scientific language; the terms used are specific to concepts, models and theories.
- information from secondary or tertiary sources which is written in your own words.
- objective, unbiased language; avoid subjective and emotional or persuasive writing (Table 1.8.3).
- concise language—avoid unnecessary repetition and express ideas in scientific language. Scientific language allows more details, knowledge and understanding to be communicated in fewer words. Use shorter sentences that are less wordy (Table 1.8.4).

The 'method' part of a report is often written in the past tense as the experiment was conducted in the past.

Table 1.8.4 shows some examples of more concise wording.

TABLE 1.8.2 Examples of first-person and third-person narrative

First person	Third person
I put 50 g of marble chips in a conical flask and then added 10 mL of 2 M hydrochloric acid.	*First, 50 g of marble chips was weighed into the conical flask and then 10 mL of 2 M hydrochloric acid was added.*
After I observed the reaction, I found that …	*After the reaction was completed, the results showed …*
My colleagues and I found …	*Researchers found …*

TABLE 1.8.3 Persuasive writing versus scientific writing styles

Persuasive writing examples	Scientific writing equivalent examples
Biased and subjective language: *The results are extremely bad/atrocious/ wonderful etc.* *This is terrible because …* *This produced a disgusting odour.* *Health crisis!*	Unbiased and objective language: *The results showed …* *The implications of these results suggest …* *The results imply …* *This produced a pungent odour.* *Health issue*
Exaggeration: *The object weighed a colossal amount, like an elephant.*	Non-emotive language: *The object weighed 256 kg.*
Use of everyday or colloquial language: *The bacteria passed away.* *The results don't …* *The researchers had a sneaking suspicion …*	Use of formal language: *The bacteria died.* *The results do not …* *The researchers predicted/hypothesised/ theorised …*

TABLE 1.8.4 Examples of verbose and concise writing

Verbose writing	Concise writing
Due to the fact that …	*Because …*
Smith undertook an investigation into …	*Smith investigated …*
It is possible that the cause could be …	*The cause may be …*
end result …	*result …*
In the event that …	*If …*
shorter in length …	*shorter …*

To produce a fluent report, the scientific language must be used without error so that the reader understands the meaning of the information easily. Refer to the glossary at the end of the student book or to the subject matter sections of the syllabus for the correct scientific terminology. Refer to the syllabus ISMG to identify the cognitive verbs used in the descriptors to produce the appropriate response. For example, you will need to write more extensively if you are asked to 'discuss' or 'explain' compared to 'identify'.

Scientific representations

Chemical or nuclear structures, equations and diagrams are an efficient way of presenting complex data and explaining concepts. Flow charts, graphs, tables and photographs are also used. Ensure you include:

- a descriptive title
- labels, captions or descriptions
- numbering, for example, Figure 1, Figure 2 etc. or Table 1, Table 2 etc.
- a source if the work is not your own or is adapted from work that is not your own.

SCIENCE JOURNAL

There is a lot of information to record during the student experiment or research investigation so it would be best to keep a **scientific journal**. Entries in your journal should include the following features:

- the date of entry
- ideas, observations, proposals, questions
- background information you researched for the task
- new terms and definitions
- refinements
- results, data, evidence, variables
- explanations, ideas, observations (including diagrams)
- limitations, conclusions, further investigation.

A journal holds a record of information used during the process of the scientific method (Figure 1.8.1). You will not know what is vital information until your experiment is complete and summarised into the scientific report. Data and graphs may be saved digitally, so reproduce a sketch in your journal that you can annotate with your thoughts. You may choose to prepare a page or two each for the four key sections of the task (eg. for IA2: Forming, Finding, Analysing, Interpreting and Evaluating) or use proposed report headings (eg. Rationale, Research Question etc.).

Researched and recorded information in your journal will be used for the Rationale; to justify the modifications to the methodology; to provide a reason for collecting data; to inform risk, ethical and environmental management; and to collate and process the data. It will also inform the interpretation of the evidence (results) and conclusion. Remember, parts of the Rationale (planning) and the data collection may be completed with your group and shared; the rest of the task is individual and so is your journal. A journal is not an assessed part of the task but will likely be reviewed by your teacher as a progress check and to confirm that the work is yours. Depending on the size of the journal, it may be copied and attached in the Appendix of your report.

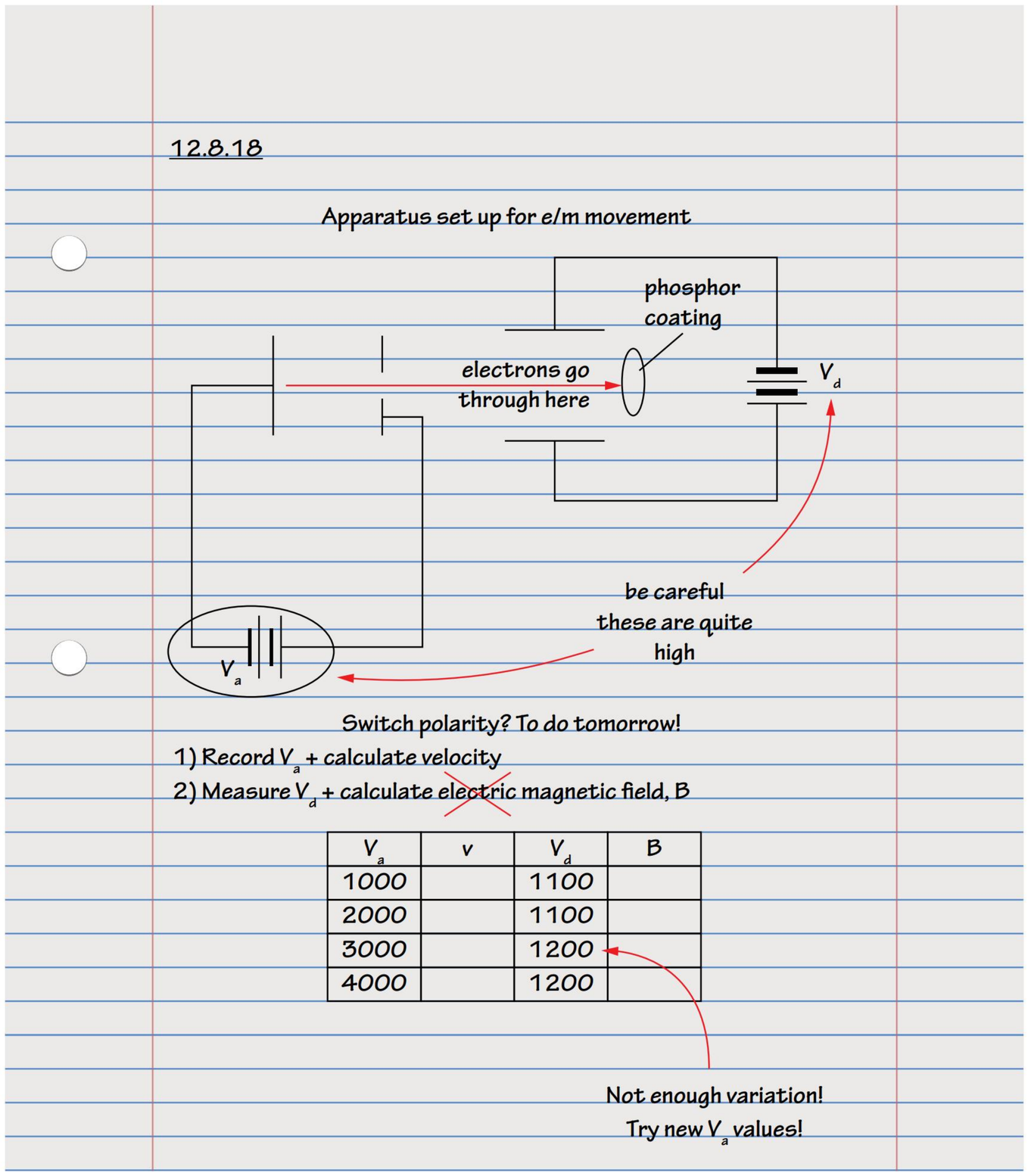


FIGURE 1.8.1 A journal entry with the journal entry date, titles and apparatus used in preparation for an experiment. There will be numerous journal entries on any given date, and they should have their own titles. Also, the same titles will appear on different entry dates as research continues on specific topics.

Journal entries can take different formats. Sometimes one form of recording information provides more details than others. Note taking is not limited to words. Figure 1.8.2 presents the same information in different ways.

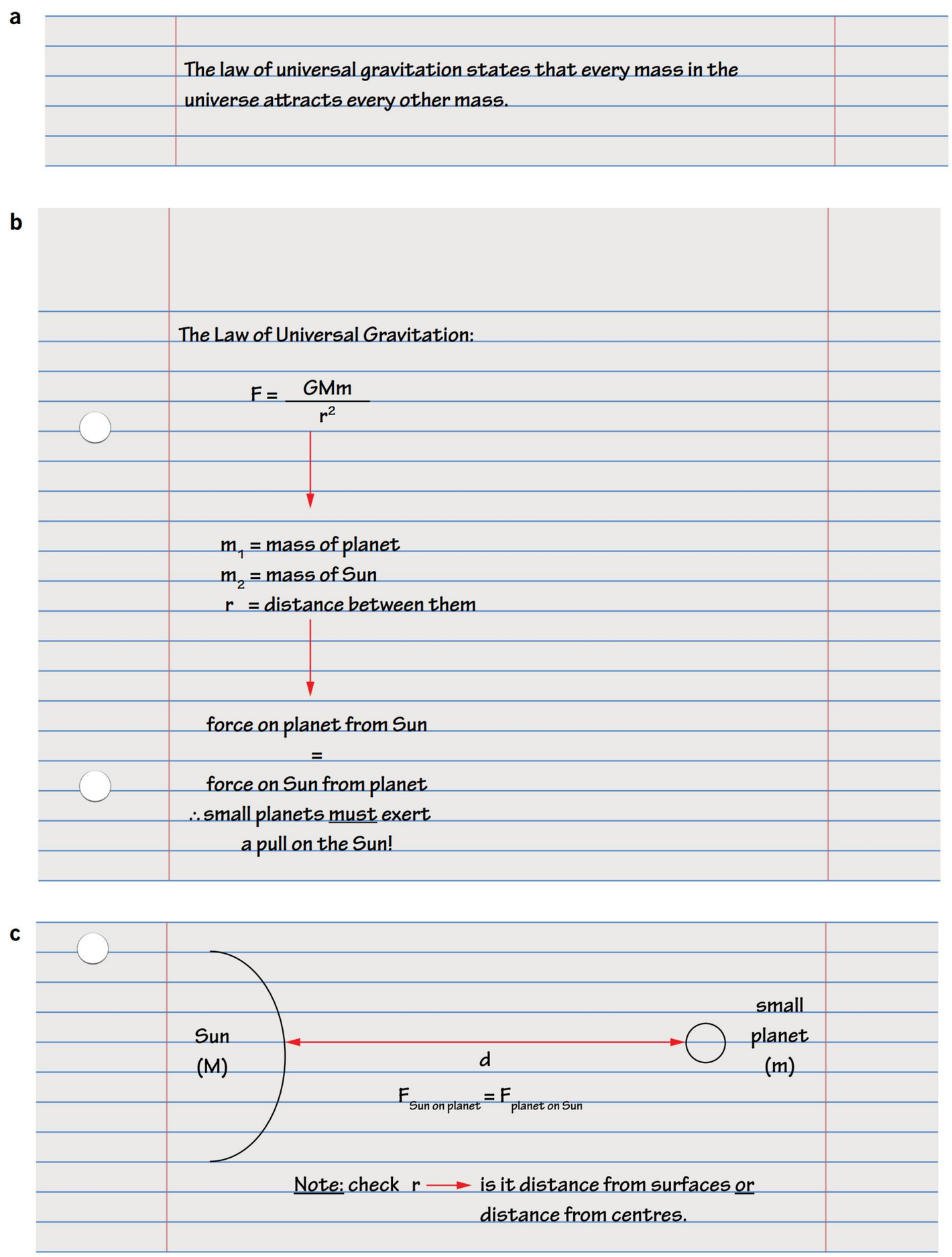
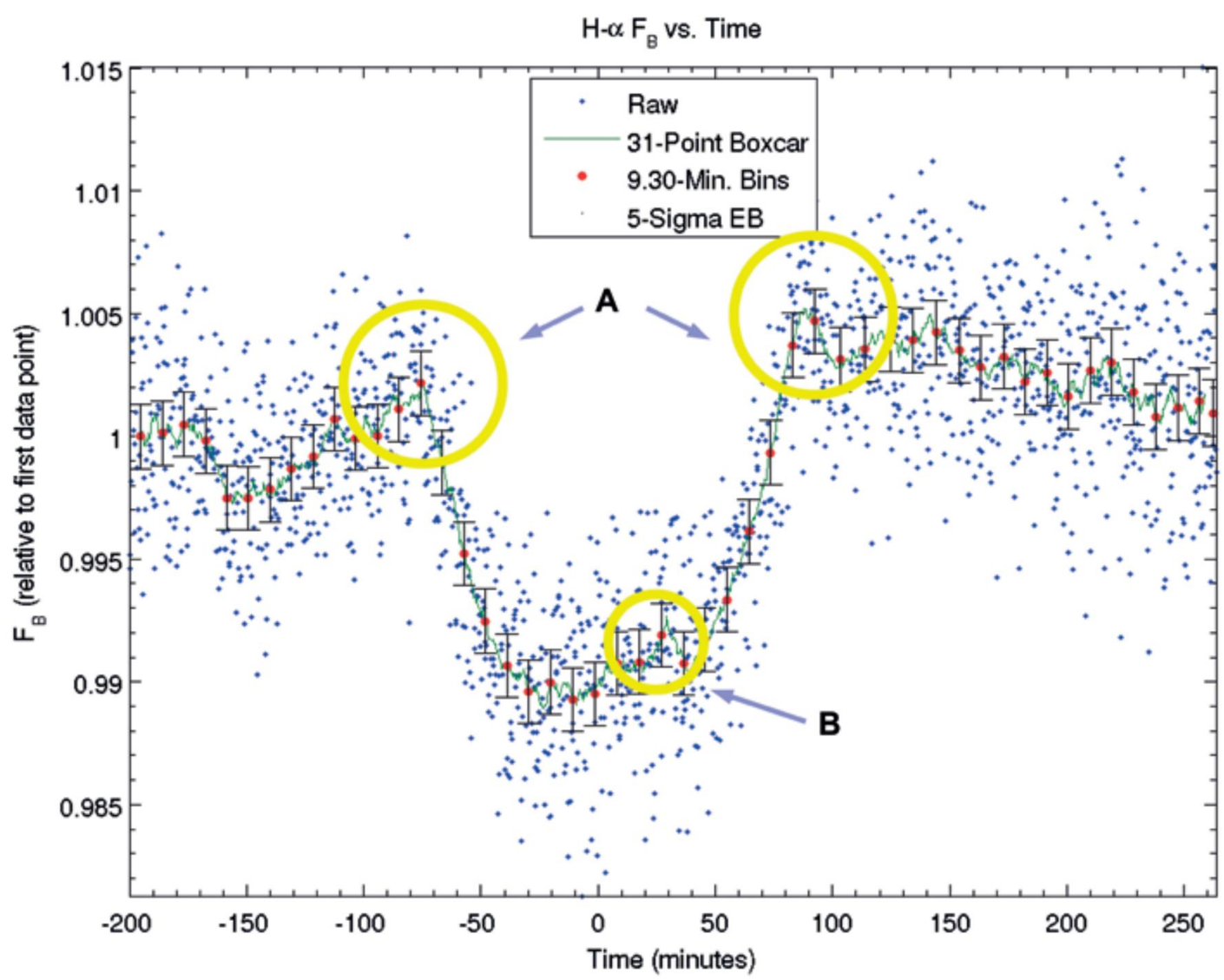


FIGURE 1.8.2 Sample page from a journal explaining Newton's law of universal gravitation (a) in the claim that small planets exert a pull on the Sun, (b) in a flow chart as a schematic to unpack the above claim, and (c) in a diagram

When recording results, data or evidence in your journal, be critical and interpret the data as it is collected. In this way, errors in the method are identified, or sample size can be adjusted, if needed. If a given group member has the recording task, it is vital that the dataset is passed to all group members before leaving the laboratory. Add this information directly into your journal and annotate with your own comments. Figure 1.8.3 shows examples of research evidence and how they can be reinterpreted for a journal entry. Figure 1.8.3a is the original evidence the student found through research and Figure 1.8.3b is the student's notes and interpretation of the evidence. Notes in your journal can also include:

- specific details and your interpretation of significant values
- the trend or pattern, and a statement of whether this is the expected one
- the comparison or difference between one set of values and another
- the statistics used to establish the significance and the author's interpretation.

a



b

21-8-17
This is the light curve -> F_B (flux or intensity) of the star DS16402 over 7½ hours, in hydrogen-alpha or 656 nm wavelength.

The features are : a big dip from −80 minutes to +50 minutes

: the brightness (?) appears to be larger after the planet had passed than before it passed (marked as "A")

: There is a smaller dip at about −150 minutes -> not sure why or if it is important.
http://user.astro.columbia.edu/~astrobio/Transit_detection.html

Statistics and Analysis
Red dots = averaged data over 9½ minutes with error bars ✓
Blue dots = raw data ✓ (no error bars?)
Box car = ?

22-8-2017
Box car = A method of smoothing data recorded over a time interval.
e.g. over 31 samples in this example
http://sunnytek.net/admin/xiazaifiles/20101141039205 22.pdf

FIGURE 1.8.3 (a) An example of original evidence found during research. (b) An example of a student record of their interpretation of the evidence found in the resource.

REFERENCING SOURCES

When gathering scientific evidence for a scientific inquiry such as Student Experiment and Research Investigation, source it from reputable publications such as:

- your textbook and practical manual. This should be your first source of reliable information.
- scientific journals and magazines: research papers and scientific reviews. Common commercial science magazines that you might find in your school library include *Double Helix*, *Cosmos*, *Scientific American* and *New Scientist*. Scientific journals are peer-reviewed which gives them credibility.

- podcasts and websites. Electronic sources include online scientific organisations such as CSIRO, NCBI, AIMS, Bioscience (Oxford Academic) and other university publications and press. In general, use websites that are .edu, .gov or .org. Many government and privately funded science organisations publish material, along with not-for-profit scientific organisations. Websites may direct you to magazines and scientific journals, podcasts, blogs and videos.

In the syllabus, you are asked to "discuss and evaluate the validity and reliability of evidence" (Science Inquiry skills). When selecting and using sources of information and evidence, follow these guidelines:

1 Confirm that it is relevant.
   - **a** Check that it contains information that is specifically related to the inquiry.
   - **b** Check that the evidence and information are pertinent to the variables of the inquiry.

2 Assess its reliability.
   - **a** Is it current/recent information?
   - **b** Is it correct in its understanding of relationships?
   - **c** Is the evidence in agreement with other sources?
   - **d** Check credibility and bias; consider who the author is, their qualifications, expertise and possible affiliations.
   - **e** Evaluate the methodology, including what variables were controlled or measured.

It is not necessary that each of your sources fulfill all of these requirements. Each source will have strong and weak points. For example, we are confident that information from a peer-reviewed scientific journal is unlikely to lack credibility or contain bias because the review process is undertaken by experts in the field. However, it may have been produced 10 years ago, and so scientific information and relationships may not be up to date. Also, podcasts or science magazines for school students may contain a wide array of interesting real-world examples but not explain the scientific understandings in sufficient detail. An informed discussion of these types of issues is part of the evaluating section of the Research Investigation. Some resources are available by paid subscription, so use advice from your school librarian about free resources or join your local library.

All quotations, documents, publications and ideas used in your investigation need to be acknowledged in the reference list in order to avoid plagiarism and to ensure creators are properly credited for their work. When using sources to explain concepts or review data, ideas must be written in your own words (see plagiarism, below). References and acknowledgements show that you have read widely, give credibility to your study and allow the reader to locate information sources should they wish to study it further.

Plagiarism

Plagiarism is using other people's work without acknowledging them as the author or creator. To avoid plagiarism, include a reference every time you report the work of others, for example, at the end of a sentence or following a diagram. If you use a direct quotation from a source, enclose it in quotation marks. This will ensure you give credit to the original author and it will enable the reader to find the original source.

Information taken from a source should be rewritten in your own words. It can be difficult to reword information in your own words, some examples are shown in Table 1.8.5. A useful strategy is to read the information, understand it, then, without looking back at the source, take notes in your journal. Notes that are detailed and have full explanations will be useful when you refer to them later to write the report.

TABLE 1.8.5 Suggestions for rewording information.

Source information:
"It can be expected that the days will be warm and the nights will be cool over the next three days due to the high pressure system moving across the region."

Strategy to change source information	Reworded information
The order of information can be swapped- the object (the warm days and cool nights) with the reason (high pressure system).	Due to the high-pressure system moving across the region, the days will be warm and the nights will be cool.
Some words can be changed such as adverbs, nouns, verbs, adjectives.	It has been predicted that during the daytime it will be warm while the evenings will be cool for about three days, as a high-pressure system travels over the region.
Information can be elaborated to explicitly outline information.	The weather forecast expects (or, made a prediction based on computer simulations) that the temperature during the day will be warm (22-25°C) and the evenings will be cool (below 12°C) due the high-pressure system (or, weak high-pressure system), which dissipates clouds and allows direct sunshine to warm Earth's surface; however, in the evenings this system brings cool air from higher altitudes, which is no longer warmed by the sun.

Referencing

There are several different referencing styles, such as Harvard or APA. The sources of information must be acknowledged using a referencing style that is suitable for the purpose of the investigation. Check the preferred referencing style or convention of your teacher for in-text referencing and a complete a **reference list**. APA (American Psychological Association) style is the most commonly used referencing style.

A bibliography is a list of all the sources used during the research to develop understanding (including information in the journal) even if the information was not used directly or explicitly in the scientific report. A reference list only lists the sources used and cited (or in-text referenced) in the scientific report. As such, a reference list is the minimum requirement and you may choose to extend this to a bibliography. The sources must be listed at the end of the report in the style consistent with your style of referencing.

Compile all references you use both directly in the scientific report or in the gathering and development of the information in a separate document as you conduct the investigation. This will save you time later. Word processing programs, such as Microsoft Word®, and other online tools make writing a reference list easier by automatically formatting references in the referencing style of your choice. Always check that this tool has formatted correctly.

In-text citations

Each time you write about the findings of other people or organisations, you need to provide an in-text citation and provide full details of the source in a reference list. The Vancouver style of referencing uses sequential numbering of the references, which are either stated [1, 2 …] etc or as subscripts after the information that is being referenced. Each individual work by the same author, even if it is published in the same year, has its own reference number. Whereas, Harvard and APA style, in-text citations include the first author's last name and date in brackets (author, date).

The following examples in Table 1.8.6 show the use of in-text citation and the corresponding reference list entry for an article in a journal in APA style. The format varies slightly according to the type of document or source you are referencing. Useful guides can be found online including many university websites.

TABLE 1.8.6 Example used of in-text citation.

Source of information and example of reference in text	Format for listing references and example of a reference as written in the reference list
Research article or review article in a scientific journal: A single atom of the rare-earth metal holmium has been made into the world's smallest, stable magnet. This was then used to make an atomic hard drive, in which each holmium atom stored one bit of information (Natterer et al., 2017).	Author, initials. (year). Title of article. Journal title, volume number (issue number), page numbers. Digital object identifier (doi) or URL Natterer, F., Yang, K., Paul, W., Willke, P., Choi, T., Greber, T., Heinrich, A., & Lutz, C. (2017), *Reading and writing single-atom magnets.* Nature, 543, 226–228.
Book: Hawking (1988) discusses the theories of general relativity and quantum mechanics and seeks to describe a unifying theory that combines these.	Author, initials. (year). Title of book (edition, if not first). Publisher. Hawking, S., (1988). *A brief history of time: From the big bang to black holes*. Bantam Books.
Online article or page: A layered crystal (created with hafnium oxide and zirconium oxide) reduces the required voltage by around 30% (Perfetto, 2017).	Author, initials/name of organisation. (year). Title of webpage or web document. URL Perfetto, I., (2022, April 1). *New crystal could help transistors run on less power.* Cosmosmagazine.com. https://cosmosmagazine.com/technology/ computing/crystal-for-transistors/

USING AI IN RESEARCH AND WRITING

Generative AI (or just AI) uses chatbots or digital assistants that you can communicate with using fairly natural language to access information in Large Language Models (computer models trained on vast amounts of data). These typically generate text, and some models can generate images, video and audio.

AI can be great for brainstorming ideas about investigations, generating practice questions and generating data for investigations. However, you must follow guidance from your teacher or school on how you can use AI in your work. You could be penalised by your school for using AI-generated material without permission or acknowledgement. It's also important to understand the limitations of AI-generated text.

> Check with your teacher before using AI in your work.
>
> Acknowledge use of AI using referencing conventions.
>
> Always fact check AI-generated text and references.

Limitations of AI-generated text

Large language models are engineered to match patterns of words, but they cannot understand the meaning of your prompt or the output text. They produce text that is similar to patterns of words in the prompts and outputs they have been trained on.

This can result in text that sounds knowledgeable and authoritative but does not mean much when you examine it or try to rephrase it in simple language. AI can hallucinate – i.e. make up statements – and this can be obvious or subtle. For example, AI can give correct answers to questions it has generated but give the wrong explanations.

The data that the model is trained on is not necessarily scientifically accurate, so generated text could be incorrect or biased. AI can be prompted to provide references, but these are often not reliable.

AI-generated answers may not model the complete response that aligns with the scope and scale of the syllabus. In class, you will have developed an understanding of the scientific concepts described in the syllabus. In this way you can check the level of information and accuracy provided in an AI-generated response.

Referencing AI sources

You must properly acknowledge the use of AI in your work. Some AI tools provide a URL that will link to generated text. If yours does not, it's a good idea to include the prompt you used and the AI output as an appendix to your work. The following are sample ways to reference AI-generated text (Table 1.8.7).

TABLE 1.8.7 Examples of ways to reference AI-generated text

Referencing style	General format	Example
APA	Author. (Year). Title of software program (Version). Date. URL. Appendix.	OpenAI. (2024). *ChatGPT* (20 June version) [Large multimodal model] https://chat.openai.com/chat or 'see Appendix for prompt used and output generated'.
Chicago	Footnote number. AI tool used, Month Day, Year, Creator of tool, URL, Appendix.	1. Text generated using GPT-4o, June 20, 2024, OpenAI, URL or 'see Appendix for prompt used and output generated'.

Prompting an AI digital assistant

Learning to write effective prompts is essential to get good results from AI. There is no perfect way to write a prompt, but using one of the many frameworks can be useful. Keep the instructions simple – for example:

- role (who the chat assistant is being, e.g. policy maker, marketer, consumer)
- task (what output you would like, e.g. an article, summary, set of questions)
- format (what it should look like, e.g. bulleted list, table, graph)

For example: I am a government policy maker working on energy strategy. Give me a one-page summary of pros and cons of using nuclear power in Australia. Consider cost, climate change, security, the environment and First Nations' perspectives in your answer. Present the summary in bullet points and include accurate references for all data.

If necessary, you can refine the results using further prompts. Note that chat assistants are not predictable, and you can get different results using the same prompt.

MULTIMODAL PRESENTATIONS

Student experiments and research investigations are focussed investigations resulting in a conclusion related to the initial question posed. In schools, the process occurs over a number of lessons but in research science a project can continue for weeks, months or years. The reporting of the final findings is usually a written report published in a scientific journal but can also take place at a scientific conference. In the Queensland Physics syllabus, you are also provided this flexibility in the form of a multimodal presentation as an alternative to the written report.

It is important to note that this mode gives you an option for the final presentation of the task only. All criteria and descriptors in the Instrument Specific Marking Guide relating to forming, finding, analysing and interpreting/evaluating need to be met as described in Parts B and C. Multimodal presentations must include at least two modes of delivery at the same time, have a maximum time of 11 minutes and a maximum of 2000 words. Your two modes are likely to be visual poster or digital presentation and verbal (speech). For average speaking speed, 11 minutes will equate to around 1600-1700 words. Your teacher will need the poster or digital presentation printed and a printed script; they may record your presentation. Another option is to use the audio record function in the presentation software. These aspects of assessment will be identified by the school as their endorsed task(s).

Some considerations regarding the speech are:

- engage and effectively communicate with the audience
- use a clear structure; it is suggested to follow the outline of a written report (see headings provided in Part B)

- interact with your presentation or poster to point out important aspects
- while it is not advised to speak on a tangent or set up a conversation with the audience, it would be possible to ask the audience if they have any questions
- use a strong confident tone
- bring your own timer to avoid going over time.

Some considerations regarding the visual presentation:

- each slide should have a clear focus with minimal text (6-7 lines per slide, 6-7 words per line). Use minimum 24 font so that the audience can read it clearly.
- present a single graph or table per slide. For graph axes or annotations in smaller font you should read this information.
- use a consistent design or theme.

Some considerations regarding the poster:

- use a presentation size large enough to include all your graphs, figures and text.
- make the poster 'flow' so the reader clearly follows the investigation from planning through to concluding and evaluating.
- allow your audience some time before the presentation to view the information and allow them to formulate questions.

Communicating experimental or research findings is an integral part of a scientist's work. Irrespective of the time span of the investigation, there is a sense of achievement when the results are made known, especially when the process requires you to relate to the topic in depth. By choosing a verbal presentation, you are able to share this journey with the audience.

1.8 Review

SUMMARY

- Scientific reports use scientific language and representations.
- The language of scientific reports is concise, objective and written in the third person.
- The scientific visual representations include tables, charts, graphs, tables, illustrations.
- Visual representations include headings, labels, captions, descriptions, numbering (if more than one item).
- A science journal is a useful tool for recording detailed information and sources during an investigation.
- Write using your own words to avoid plagiarism.
- Acknowledge sources and any references to the work of others by including a reference list.
- If using AI for scientific research ensure information is checked against other sources, avoid plagiarism and acknowledge the source.

KEY QUESTIONS

Describe

1 Explain the difference between a bibliography and a reference list.

2 Describe what plagiarism is and indicate why it is unacceptable.

Apply

3 List the information that should be recorded about an online source in your journal.

4 Explain the benefit of keeping a scientific journal.

Analyse

5 Rewrite the following text in your own words.

a A group of patients was administered adrenaline during a cardiac arrest to determine if adrenaline would improve patient outcomes. There was no statistically significant improvement in patient outcome between patients who received adrenaline and those who did not.

b A team of scientists from the Oregon Health and Science University and Korea's Institute for Basic Science successfully repaired a defective gene in human embryos. The gene that was targeted caused a heart defect, known as hypertrophic cardiomyopathy, which causes sudden death in young adults.

1.9 Syllabus requirements

The student experiment (IA2) requires you to undertake the full scientific method. The Physics General Senior Syllabus 2025 states that this process begins with a practical conducted during class or viewed online. This practical will be modified to conduct your own experiment. It is recommended that during the class practical you record your observations, queries and thoughts as well as collecting and processing data. These notes can be used to lead to a research question for the student experiment. This task assesses syllabus objectives and science inquiry skills and relates to student experiment objectives and specifications from the Physics General Senior Syllabus 2025.

The student experiment constitutes 20% of the total assessment and may be presented in:

- written form (such as scientific report), up to 2000 words, or
- multimodal presentation form (at least two modes delivered at the same time), up to 11 minutes.

In the modules that follow, you will find a guide to a scientific method and an outline for producing a student experiment report.

INSTRUMENT-SPECIFIC MARKING GUIDE

Student responses are assessed against an instrument-specific marking guide (ISMG). In developing your experiment and planning your response, it is important to always have in mind the assessment objectives, and in particular the characteristics that are described in the performance level descriptors.

- The ISMG has four criteria (criterion):
  - forming
  - finding
  - analysing
  - interpreting and evaluating
- Criteria have performance levels, against which the qualities of the response are assessed.
- A performance level consists of a descriptor and mark or mark range.
- The performance level descriptor describes the characteristics that are demonstrated by a response at this quality.
- The ISMG criteria, and elaborations of each are shown in Table 1.9.1, for the highest performances.

TABLE 1.9.1 Alignment of syllabus criteria, objectives, descriptors and marks with the modules of Part B

Criteria	Assessment objectives	Instrument specific marking guide (ISMG) descriptors – Criteria are demonstrated by:	Marks	Module
Forming	1. Describe ideas and experimental findings about gravity and motion, or electromagnetism. 2. Apply understanding of gravity and motion, or electromagnetism to modify experimental methodologies and process data. 6. Investigate phenomena associated with gravity and motion, or electromagnetism through an experiment.	• a considered rationale for the experiment • justified modifications to the methodology • a specific and relevant research question • a methodology that enables the collection of sufficient and relevant data • appropriate use of genre and referencing conventions	5	1.10 1.8
Finding	1. Describe ideas and experimental findings about gravity and motion, or electromagnetism 6. Investigate phenomena associated with gravity and motion, or electromagnetism through an experiment.	• considered management of risks/ethical issues/ environmental issues • collection of sufficient and relevant raw data • fluent and concise use of scientific language and representations	5	1.11
Analysing	2. Apply understanding of gravity and motion, or electromagnetism to modify experimental methodologies and process data. 3. Analyse experimental data about gravity and motion, or electromagnetism	• correct and relevant processing of data • thorough identification of relevant trends/patterns/ relationships • thorough and appropriate identification of the uncertainty and limitations of evidence	5	1.12
Interpreting and evaluating	4. Interpret experimental evidence about gravity and motion, or electromagnetism 5. Evaluate experimental processes and conclusions about gravity and motion, or electromagnetism	• justified conclusion/s linked to the research question • justified discussion of the reliability and validity of the experimental process • suggested improvements and extensions to the experiment that are logically derived from the analysis of evidence	5	1.13
Total			**20**	

The final report for the student experiment may be organised under the criteria headings in the instrument-specific marking guide (ISMG); forming, finding, analysing and interpreting and evaluating. However, this is not mandated, and you may elect to organise your report in a different but logical order using alternate headings.

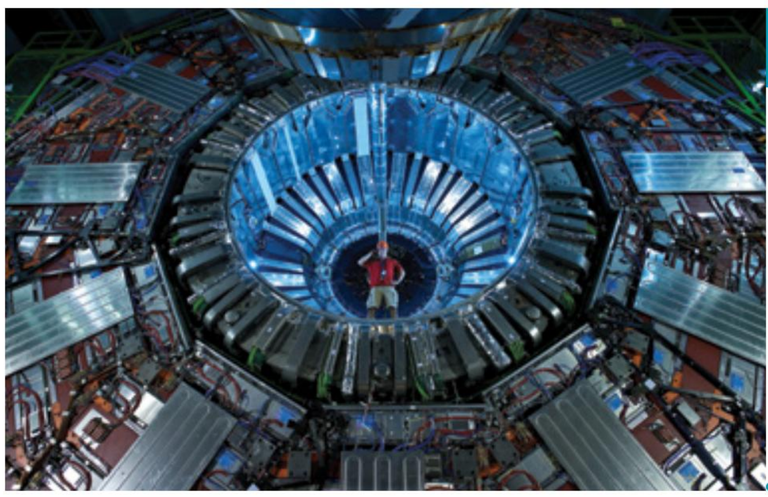
Note that items such as title or contents pages, the abstract, appendixes, bibliography or reference list and in-text references are not included in the word count. The contents of the appendix are not used for determining levels of achievement.

The headings and sub-headings in Table 1.9.2 show one possible structure of a student experiment report, and alternate positionings of the conclusion section (*).

TABLE 1.9.2 Possible student experiment structure

Forming	Rationale
	Research question
	Modifications
Finding	Risk assessment
	Raw data
Analysing	Sample calculations
	Processed data
	Analysis
Interpreting and evaluating	Conclusion*
	Evaluation of experimental process (reliability and validity)
	Improvements and extensions
	Conclusion*
	Reference list/Bibliography
	Appendix

1.10 Forming



BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- understand how to identify and modify an experimental investigation
- research relevant background information that informs the research question
- develop the investigation by forming a research question that includes specific variables
- justify modifications to the original experiment.

RATIONALE

The student experiment uses a completed class practical or simulation as a basis for further experimentation. This means that the rationale will show an idea flow which begins with an original experimental result and uses scientific reasoning to propose a new and related question (Figure 1.10.1). Often the same or a similar experimental apparatus is used but independent and/or dependent variable(s) are altered. Conversely, a new experimental design and equipment is used to investigate the topic.

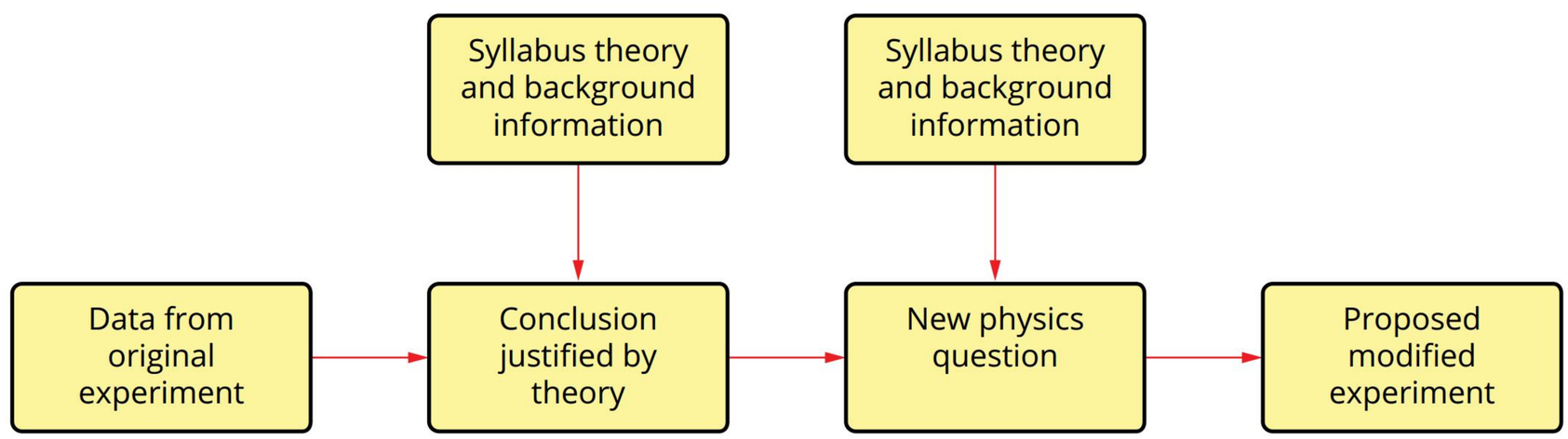


FIGURE 1.10.1 A new physics question is developed from physics understanding and the result of the original experiment.

Background information

The physics concepts of both the original experiment and the proposed new experiment need to be described but it is important to restrict this to the necessary detail; a full topic explanation or literature review is not required. Make sure that key syllabus concepts are included using relevant equations, structures and diagrams. Background concepts need to be referenced by scientific literature using in-text referencing. You will need to read widely but are advised to limit your use of physics concepts that are beyond the scope of the syllabus. If your original experiment and proposed new experiment cannot be explained using syllabus concepts from the appropriate unit, you will need to change your experimental focus. While science understanding of Unit 1 and Unit 2 are formative in the concepts of Units 3 and 4, a summative student experiment cannot be based on science understanding of Units 1 and 2. Your explanation of background information demonstrates understanding and knowledge of the direct, and possibly indirect, relationship between the independent and dependent variables, and controlled or measured variables.

The syllabus states that the task requires students to: 'research relevant background scientific information to inform the modification of the research question and methodology'.

Here we see:

- 'relevant', which means background scientific information relevant to the syllabus as well as relevant to your experiment
- 'inform', which means you have used science concepts to identify a new experiment

- 'modification', since the new experiment is related to the first one but the variable(s) and/or method are modified
- 'research question', which refers to a specific research question with proposed dependent and independent variables
- 'methodology', which relates to the details of how you plan to conduct your experiment using scientific method.

Group planning

Parts of the experiment can be completed with your group. For instance, it is appropriate to discuss the findings of the original experiment to be clear about the relationship shown in the data. Also, the group should discuss changes to the method or dependent and independent variables which may be appropriate. However, the rest of the investigation, including analysis, evaluation and report writing, is an individual task.

Discuss with your peers the ideas already learnt in class about the topic and possible or expected relationships which could be investigated (Figure 1.10.2). This relationship will be the focus of your research question. In addition, you may propose a refinement of equipment or methodology which will need to be discussed and clarified with your teacher. Check that your school laboratory has the resources for you to perform the experiment or investigate the topic. Choose a topic that can provide clear measurable data that shows how variable y depends on variable x.

Consider the following when developing the modified experiment:

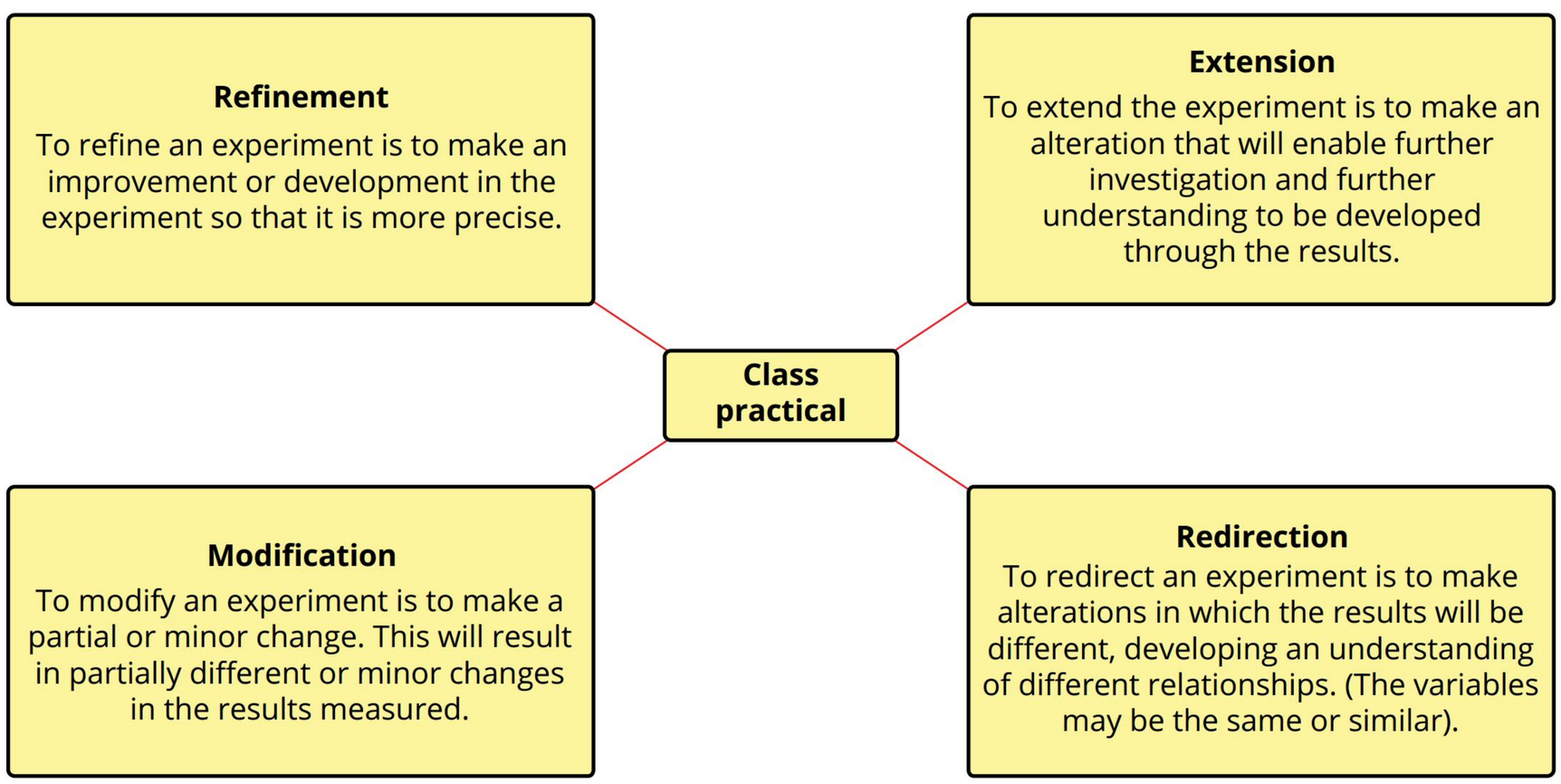


FIGURE 1.10.2 Changes that can be made to a class practical to develop the student experiment

Table 1.10.1 shows examples of modifying an original experiment into a topic of interest for a student experiment.

TABLE 1.10.1 Examples of modifying a practical into a student experiment

Original experiment	Possible modified experiments
Conduct an experiment to investigate the proportional relationship between heat and temperature change.	Does the proportionality between heat and temperature change vary with mass?
	Is the accuracy of the proportionality constant between heat and temperature change improved by additional trials?
	Can the experimental method be used to determine the proportional relationship between heat and temperature change for other substances?
	Can the apparatus or method be altered to limit heat loss and increase the accuracy of the investigation?

Defining the variables and data collection

The factors that can change during your experiment or investigation are called variables. An experiment or investigation determines the relationship between variables by measuring the results. There are four categories of variables (Figure 1.10.3). You should have only one independent variable. Otherwise, you could not be sure which independent variable was responsible for changes in the dependent variable (the results). It is best to think of a single variable (independent variable) that may influence the measured outcome (dependent variable). Use clear dependent and independent variables, and be specific about the number of trials. The more variables that are altered (including **measured variables** and **controlled variables**), the more complex the task becomes.

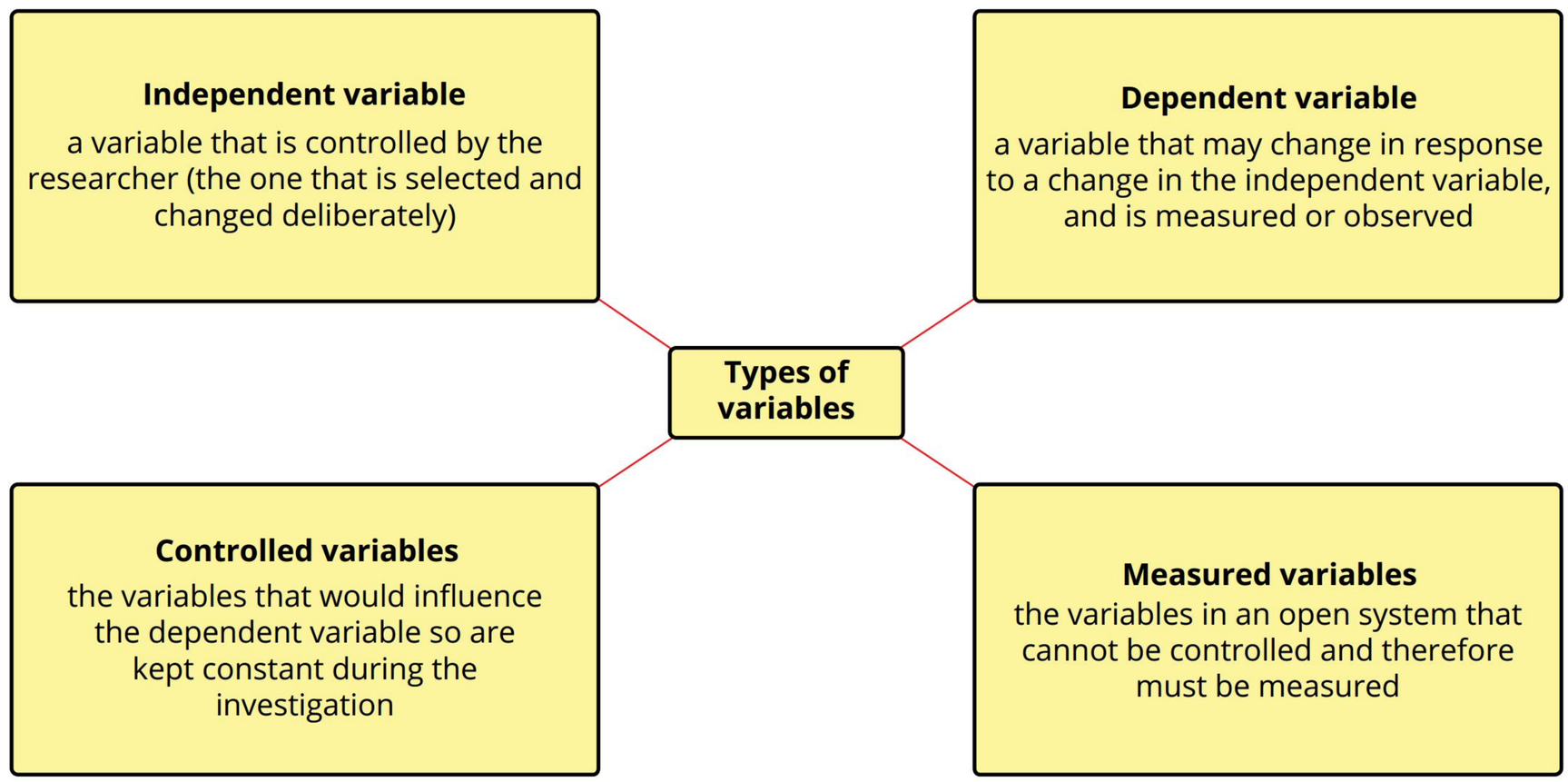


FIGURE 1.10.3 The four types of variables in experiments

To ensure an investigation is **valid**, it should be designed so that only one variable is being changed by the researcher at a time, and only one variable is changing in response. The remaining variables must remain constant so that meaningful conclusions can be drawn about the relationship between variables. In junior science we learn "Change one thing, measure one thing, keep everything else the same". In your Rationale and Research Question discussions with your group and teacher you will consider the:

- independent variable (the thing that is changed)
- dependent (measured) variable
- controlled variables (parts of the equipment, method and conditions that are constant)
- appropriate raw data that will be collected (quantitative versus qualitative), and how each will be measured, collected or controlled.

Data can either be qualitative or quantitative. **Qualitative data** is descriptive and unmeasurable, and uses descriptions or adjectives to record observations. It cannot be statistically analysed. **Quantitative data** is empirically measurable and uses instruments to record observations as numbers with units.

Qualitative and quantitative data have further subsets in each category (Figure 1.10.4).

Qualitative data: can be observed but not measured.

They can only be sorted into groups or categories such as the colour of light or shape of a magnetic field.

Nominal data

Variables are categorical variables in which the order is not important.

Example 1: the type of metal, type of apparatus

Example 2: the planets in our solar system

Ordinal data

Variables are categorical variables in which order is important and groups have an obvious ranking or level.

Example 1: the level of brightness of light globes

Example 2: the apparent brightness of stars as seen from Earth

Quantitive data: can be measured.

Height, mass, volume, temperature, intensity and time are all examples of quantitative data.

Discrete data

Variables consist of only integer numerical values, not fractions.

Example 1: the number of springs connected together

Example 2: the energy levels in atoms

Continuous data

Variables allow for any numerical value within a given range.

Example 1: the measurement of height, temperature, volume, mass and intensity

Example 2: time for cart to slide down a ramp

FIGURE 1.10.4 Quantitative and qualitative variables

Measurement of temperature requires an instrument and provides quantitative data whereas sensing the production of heat by touch provides qualitative data (Figure 1.10.5).

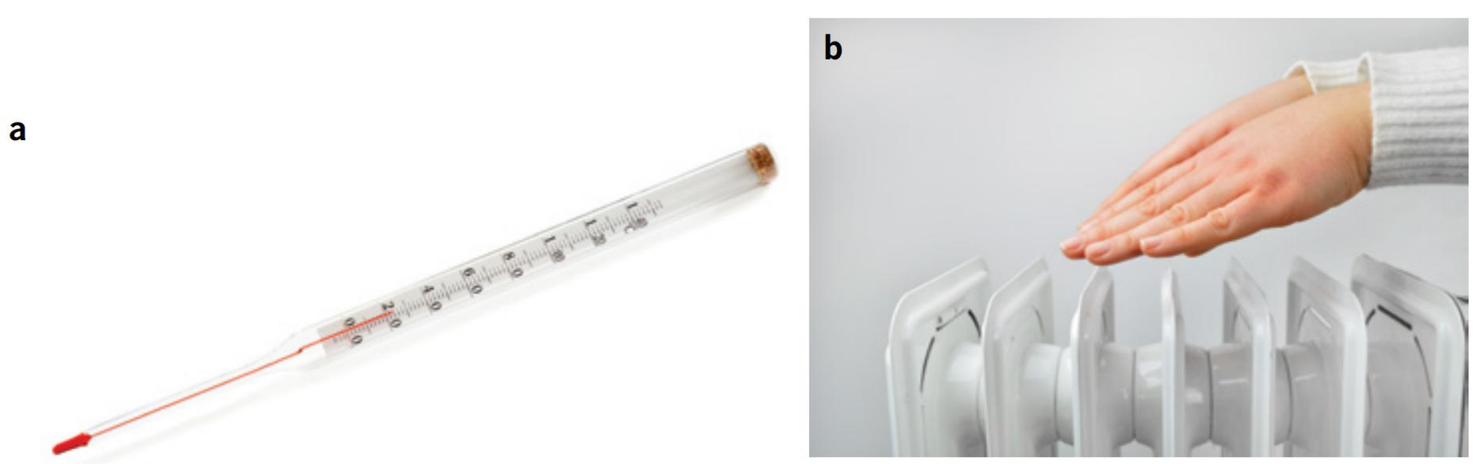


FIGURE 1.10.5 (a) Using a thermometer or a wireless temperature sensor will measure temperature empirically and provides quantitative data that can be analysed statistically. Processing empirical data can produce discrete, explicit and comparative analysis. (b) Feeling heat radiating from a heater is an example of qualitative data as it is based on personal observation. Qualitative data cannot be statistically analysed.

Depending on the experiment, it may be appropriate to record the qualitative observation (e.g. brightness of light), or to measure quantitative results (e.g. voltage).

Sourcing appropriate equipment and materials

You will need to decide on the materials, technology and instrumentation that will be used to carry out your experiment or investigation. It is important to find the right balance between items that are easily accessible and those that will obtain accurate and precise results. The precision of the chosen instrumentation affects the level of measurement uncertainty and is recorded as a ± value in the raw data table.

Sample size

Because a single measurement or experimental result could be affected by errors, replication of samples within an experiment and repeat trials are key components of reliability. A larger sample size will improve:

- the representation of the phenomenon
- the natural variation, errors and uncertainty
- the results by offering more evidence to support the experimental results
- aids with repeatability and therefore reliability.

Consider the practicalities of timing and validity of data in determining the number of trials and the number of independent variables tested. Given that 10 hours are allocated to planning the experiment, performing the experiment and writing the report, 25 trials is generally sufficient. This represents 5 different values of the independent variable, with 5 trials each.

WRITING A RESEARCH QUESTION

When you have decided on a dependent variable, independent variable, controlled variable(s) and method of testing you are ready to write your research question.

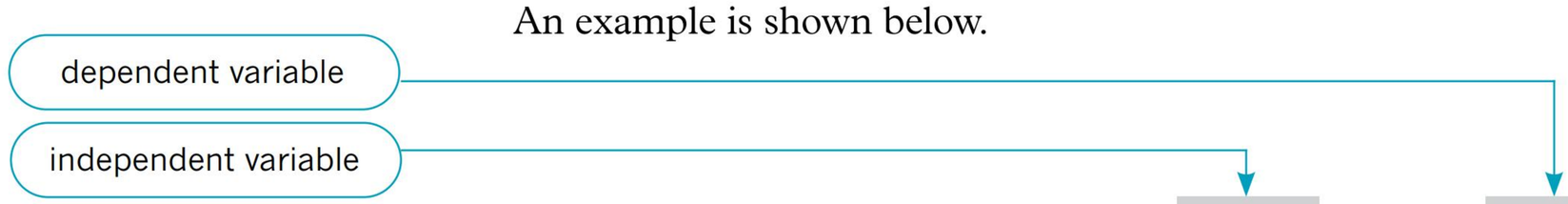
A research question directs and describes the scientific inquiry activity. Its purpose is to focus the student experiment, inform the direction of the research, and guide all stages of inquiry, analysis, interpretation and evaluation.

The question determines the experiment and the experiment is testing the question. A research question should:

- be specific and relevant to the class experiment
- clearly identify the subject matter of the experiment
- specify the scope or conditions of the inquiry
- aim to find trends or patterns of relationships between two variables.

A research question should state the independent and the dependent variables. It should ask if the independent variable will affect the dependent variable. The research question must specifically outline variables in a way that are measurable; this also allows the research question to be answered.

An example is shown below.



'What is the relationship between the length and the period of a simple pendulum if the angle of release and mass of the bob are constant?

A well-constructed research question should have the following characteristics:

- It should include measurable variables—the independent variable and the dependent variable.
- It should have a guiding word, such as *how*, *what* or *will*.
- It should be phrased so that a definitive answer can be developed.
- It should state key (not all) controlled variables or conditions.

Table 1.10.2 gives examples of constructed research questions.

TABLE 1.10.2 Structuring a research question

Guiding word(s)	Example research questions
what	What is the relationship between cross sectional area and resistance in a series circuit, if the resistivity and voltage remain constant?
will	Will increasing the mass of an object affect fall time, if the size of the object and drop height remain constant?
how	How does the amount of radiation detected 10cm from an Americium-241 source change as the amount of shielding between the source and the detector is increased?
can	Can the current within a series circuit be reduced by increasing the resistance of a component?
do/does	Does the quantity of water used in calorimetry effect the accuracy of determining the specific heat capacity of a substance?

Evaluating your research question

Once a research question has been developed, stop to evaluate it before progressing.
Follow the prompts in the chart below (Figure 1.10.6) to refine and improve it.

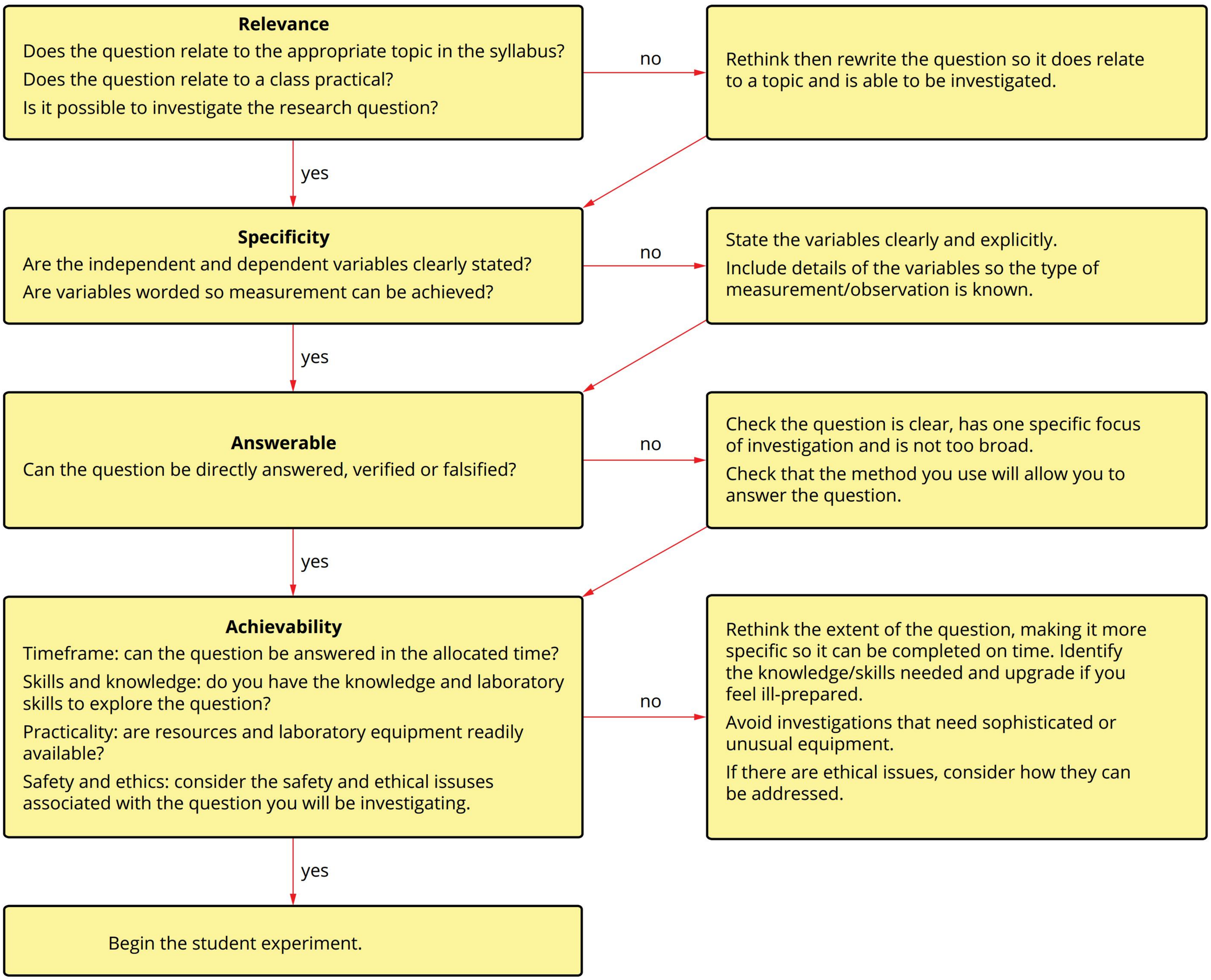


FIGURE 1.10.6 Steps to refine and improve the research question

A research question proposes a question about the relationship between the dependent and independent variables. It is a required component of the Student Experiment. A hypothesis defines the expected link between dependent and independent variables and supports the research question but is not an assessed component of the ISMG.

Formulating a hypothesis

A hypothesis may be developed. A **hypothesis** is a statement that proposes a relationship between variables and an expected result of the experiment; it is based on some level of understanding. Having completed extensive background research (rationale), you will have the means and understanding to state the expected results in the form of a hypothesis.

The student experiment does not require a hypothesis and it may not always be appropriate or beneficial. Because the hypothesis proposes a specific relationship between the independent and dependent variables, the hypothesis can either be supported or refuted by the results. Note that a hypothesis can be supported or confirmed, but not 'proved', whereas it can be disproved (refuted).

The following examples (Table 1.10.3) demonstrate the relationship between dependent and independent variables, and a research question:

TABLE 1.10.3 Research question examples

Relationship between dependent and independent variables	Research question
As the temperature of the gas increases, the volume of the gas will increase.	How does the volume of air in a syringe change as the temperature of the air is increased from 20 to 80 degrees Celsius?
The rate of reaction will increase and time for production of 25 mL gas will decrease as the temperature of the reaction mixture increases.	Does the time taken for the production of 25 mL of hydrogen gas decrease as the temperature of the solution of 50 mL 0.5 M hydrochloric acid and 5 g zinc is increased?
The accuracy of the measured molar enthalpy of combustion of ethanol will be increased by performing multiple calorimetry experiments.	Does burning different masses of ethanol (2 g, 4 g, 6 g) in multiple calorimetry experiments improve the accuracy of the determination of the molar heat of combustion?

MODIFICATIONS

The previous section shows how complex the Forming (planning) part of the student experiment is. You (and your group and teacher) will have decided on key aspects of the modified experiment—independent, dependent and controlled variables—identified a procedure and equipment for use, and written a research question. It is necessary to document each modification to the original experiment in your report and justify each proposed modification.

The methodology of your experiment is a specific step-by-step procedure which your teacher will require you to prepare prior to the experiment. However, this detail is generally not required in the report. In the modifications section, write an overview of the original method (use an in-text reference) in paragraph form and provide a written or tabulated description of the modifications proposed. Include specific details about instruments and techniques employed, and the number of trials. Each modification is justified by stating the type of change ('refine', redirect' or 'extend') and how it will improve the investigation. If possible, link each modification to random and systematic error. An example is shown in Table 1.10.4.

TABLE 1.10.4 Example modifications to original experiment with justification

	Modification	Justification
Refinement	Replacing a foam projectile with a ball bearing	Reduces the impact of drag on projectile motion, reducing systematic error from drag and random error from wind.
Refinement	Collection of more data – five trials for each value of the independent variable rather than one.	Improves accuracy by providing an average and uncertainty.
Redirection	Measuring how the strength of a magnetic field varies with angle.	Changes the independent variable to investigate another aspect of the theoretical relationship.
Extension	Measure the horizontal displacement of projectile motion between 0-degrees and 180-degrees.	Measures the behaviour across all values to see if the relationship holds across the entire range.
Refinement	Replace stop watches with video analysis.	Provides more reliable readings of time and reduces random error.

One way to modify an original experiment is to improve the precision of the laboratory equipment. With higher-precision instruments, there is less chance of error and lower uncertainty in the measurement. Table 1.10.5 demonstrates the benefits of greater-precision instruments through lower measurement uncertainty.

TABLE 1.10.5 The difference in precision between instruments: (a) a glass thermometer with a precision of ±0.5°C; (b) a measuring beaker with a precision of ±5 mL; (c) a metal ruler with a precision of ±0.5 mm (d) a digital laser thermometer with a precision of ±0.05°C; (e) a measuring cylinder with a precision of ±0.25 mL, and (f) a micrometer with a precision of 0.005 mm

Lower precision instruments

a

b

c

Higher precision instruments

d

e

f

PUTTING IT ALL TOGETHER

The following sample experiment report below is an example of a modification of the investigation of linear motion from Unit 2. This modification is no longer suitable for Unit 2 (the chosen modification is no longer linear motion, taking it outside of scope of Unit 2). This was intentionally selected to reduce the impact on student responses.

It follows the ISMG criteria and may be used as a reference tool.

An investigation into the relationship between pendulum length and period for a simple pendulum as a method of verifying the acceleration due to gravity

Rationale

Gravity is a form of acceleration and is generalised across the surface of the Earth as 9.81 m s^{-2}. (WDC for Geophysics, Beijing, 2015). This value would hold true everywhere if the Earth existed as a perfect sphere. Earth is actually an "oblate spheroid" which is bulging at the equator and flatter at the poles (WDC for Geophysics, Beijing, 2015). Furthermore, gravitational force is also somewhat dependent on mass (second law of motion) and so "the strength of gravity's pull on an object may be stronger or weaker at different locations, depending on Earth's inner structure and topography". For example, places with more mass present (e.g a mountain) will have stronger gravitational forces than places with less mass (e.g a valley) (Patel, 2023). The goal of this experiment will be to verify the expected/predicted value of gravity, 9.81 m s^{-2}.

The original experiment conducted in class was a freefall experiment where a ball was dropped from various heights (displacements) and the fall time was recorded. The experimental uncertainty was quite large (9.38 ± 0.51 m s^{-2}) only barely containing the expected value for gravity. Analysis revealed that these large uncertainties were due to the random error of human reaction time, as well as drag decelerating the falling ball. This can be seen in the drag equation below where drag (D) increases with velocity (v) (Benson, 2015):

$$D = C_d \times r \times \frac{1}{2} v^2 \times A$$

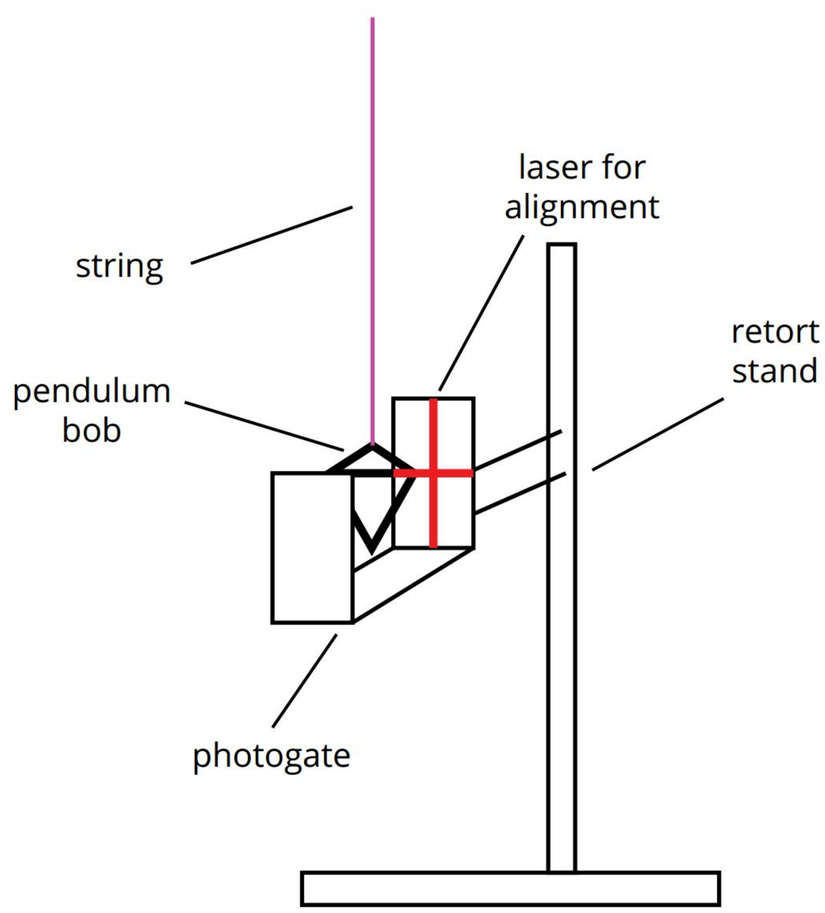


FIGURE 1 Experimental setup

To overcome these limitations, it was decided to modify the experiment to reduce velocity to minimise the effect of drag, and to remove the random error introduced by reaction time. This was achieved by redirecting the experiment to investigate a simple pendulum (Figure 1) where a bob (142.45 g mass and 23.24 mm diameter) is suspended from a string and released at an angle of less than 15° (The Physics Classroom, 2023). A pendulum was chosen as this will limit velocity while still providing a significant duration of motion under gravity. By measuring this duration with photogates, reaction time was removed as a source of error.

The equation for a simple pendulum is:

$$T = 2\pi\sqrt{\frac{l}{g}}$$

where T is the period (s) and l is the length of the string (m). Linearised this gives:

$$T^2 = \frac{1}{g} \times 4\pi^2 l$$

As such, the expected relationship between period and length is $T^2 \propto l$. The constant of proportionality is equivalent to $\frac{1}{g} \times 4\pi^2$, allowing for verification of the value of gravity.

Research question

What is the relationship between pendulum length and period for a simple pendulum if the mass of the bob is kept constant and the angle of release is less than 15 degrees?

Modifications to the methodology

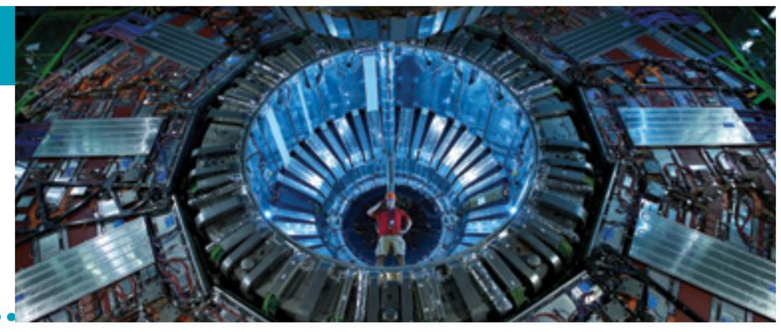
The proposed modifications to the methodology are described in Table 1.

TABLE 1 Modifications to the methodology

Modification	Justification
Redirection: Investigating the relationship between pendulum length and period	This limits velocity, which limits drag. This reduces the impact of a confounding variable allowing for increased accuracy. Pendulum length and period were chosen as these are most similar to fall time and height from the original experiment.
Refinement: Stopwatches were replaced with photogates	This removes reaction time from the experiment, improving precision.

1.11 Finding

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:



- conduct a risk assessment
- undertake an experiment encompassing sufficient and relevant data
- collect and present data.

RISK ASSESSMENT

When planning for an experiment in either the laboratory or outside in the field, it is important for your safety and the safety of others that you consider potential risks. Your report should outline potential risks, how they will be mitigated, and how they will be managed. While the key consideration is for the personal safety of the people in the laboratory, you may need to consider and include a statement about potential ethical considerations or effects on the environment if relevant to your experiment.

Your **risk assessment** will have three sections:

- hazard—the name of the item or activity that could cause risk
- risk—the possible negative outcome that could occur
- control measures—the practices or processes to avoid the risk.

Often, the original experiment will have used similar equipment and so information from its risk assessment can be used. Check with your teacher regarding new equipment that you are planning to use.

To identify risks, think about the following:

- laboratory rules of the school, for example, procedures for behaviour in a laboratory and procedures for equipment use
- the activity that you will be carrying out including physical issues such as lifting heavy objects or use of projectiles and how you will use any equipment (such as glassware) or chemicals that you will be handling, including sources of heat and electricity.
- the facilities of the laboratory. These include emergency equipment on site, ventilation of the laboratory, facilities such as a fume hood.
- the chemical codes and SDS data (Safety Data Sheet) for chemicals in use. Consider also concentrations of chemicals and hazards associated with products of chemical reactions.
- what protective clothing you should wear, e.g. lab coat and goggles.

Chemical codes

The chemicals at school or in a hardware shop have a warning symbol on the label. These symbols are a chemical code indicating the nature of the contents (Table 1.11.1). In 2017, the Globally Harmonised System of Classification and Labelling of Chemicals (GHS) was introduced in Australia for use in workplaces, including school laboratories.

TABLE 1.11.1 GHS pictograms used as warning symbols on chemical labels

GHS symbol	Use	GHS symbol	Use	GHS symbol	Use
	flammable liquids, solids and gases; including self-heating and self-igniting substances		oxidising liquids, solids and gases, may cause or intensify fire		explosion, blast or projection hazard
	corrosive chemicals; may cause severe skin and eye damage and may be corrosive to metals		gases under pressure		fatal or toxic if swallowed, inhaled or in contact with skin
	low level toxicity; this includes respiratory, skin and eye irritation, skin sensitisers and chemicals harmful if swallowed, inhaled or in contact with skin		hazardous to aquatic life and the environment		chronic health hazards; this includes aspiratory and respiratory hazards, carcinogenicity, mutagenicity and reproductive toxicity

Safety data sheets

Each chemical substance has an accompanying document called a **safety data sheet (SDS)** (Figure 1.11.1). An SDS contains important safety and first aid information about each chemical you commonly use in the laboratory. The SDS provides employers, workers and health and safety representatives with the necessary information to safely manage the risk of hazardous substance exposure.

1. IDENTIFICATION OF THE MATERIAL AND SUPPLIER

Product identifier

Product Name HYDROCHLORIC ACID - 20% OR GREATER

Supplier
Edwards & Tubbs Operations Pty Ltd
ABN: 51 444 444 444
13 Royston Vasey Street
Melbourne 3000
Australia

Emergency telephone number **1900 654 321 (ALL HOURS)**

2. HAZARDS IDENTIFICATION

GHS Classification

Classified as dangerous goods in accordance with the Australian Code for the Transport of Dangerous Goods by Road and Rail (ADG).

Classified as a hazardous chemical in accordance with the criteria of Safe Work Australia - Globally Harmonized System (GHS).

Corrosive to metals	Category 1
Skin corrosion/irritation	Category 1 Sub-category B
Serious eye damage/eye irritation	Category 1
Specific target organ toxicity (single exposure)	Category 3

SIGNAL WORD: Danger

Hazard statements
H290 - May be corrosive to metals
H314 - Causes severe skin burns and eye damage
H335 - May cause respiratory irritation

Precautionary Statements - Prevention
Keep only in original container
Do not breathe fume, gas, mist, vapours, spray
Wash face, hands and any exposed skin thoroughly after handling
Use only outdoors or in a well-ventilated area
Wear protective gloves / protective clothing / eye protection / face protection

FIGURE 1.11.1 Extracts of a safety data sheet (SDS) for concentrated hydrochloric acid. The SDS alerts the reader to any potential hazards when using a substance, including appropriate measures to reduce risk of harm.

All schools store SDS and chemical code information for materials in use in laboratories and these must be consulted when planning investigations. Online platforms such as RiskAssess allow quick access to these data bases for a planned experiment. In these types of software programs, the potential hazards for each aspect of the experiment are provided when proposed equipment and materials are listed. Handling procedures are also suggested.

It is important to note that to address the syllabus requirement to show 'considered management of risk', you need to do more than downloading a data sheet, or using risk assessment software. The syllabus specification requires you to 'conduct a risk assessment and account for risks in the methodology.' This means that, as described above, the three factors of (i) risk (ii) possible negative outcome and (iii) prevention need to be aligned and clearly presented in the report. This can be done by writing a paragraph or preparing a table (Table 1.11.2). The supporting data sheets or risk assessment files should be placed in the Appendix and key facts used in your report.

TABLE 1.11.2 Sample risk assessment table showing hazards, risks and control measures to reduce the risks

Hazard	Risk	Control Measures
neodymium magnets	May shatter if released from a distance. May pinch skin if handled improperly.	Magnets were affixed in place by teacher and taped down so they could not be moved. Safety glasses worn.
power pack	Becomes hot with use. Hazardous around liquid.	Power pack turned on briefly for data recording then turned off again immediately to prevent temperature build up. No liquids used near experiment. Group members instructed on location and use of emergency power switch.
resistor	Can become very hot and burn out if power is left on.	Power pack turned on briefly for data recording then turned off again immediately to prevent temperature build up. If resistor becomes burned out, allow to cool before attempting to replace. Group members instructed on first aid kit location and burn treatment protocol.

Risk controls

The hierarchy of risk controls is shown in Figure 1.11.2. It is organised from the most effective to least effective. The most used risk control measure that addresses the majority of risks is personal protective equipment. The least common but most protective control measure is eliminating the risk from the scientific investigation.

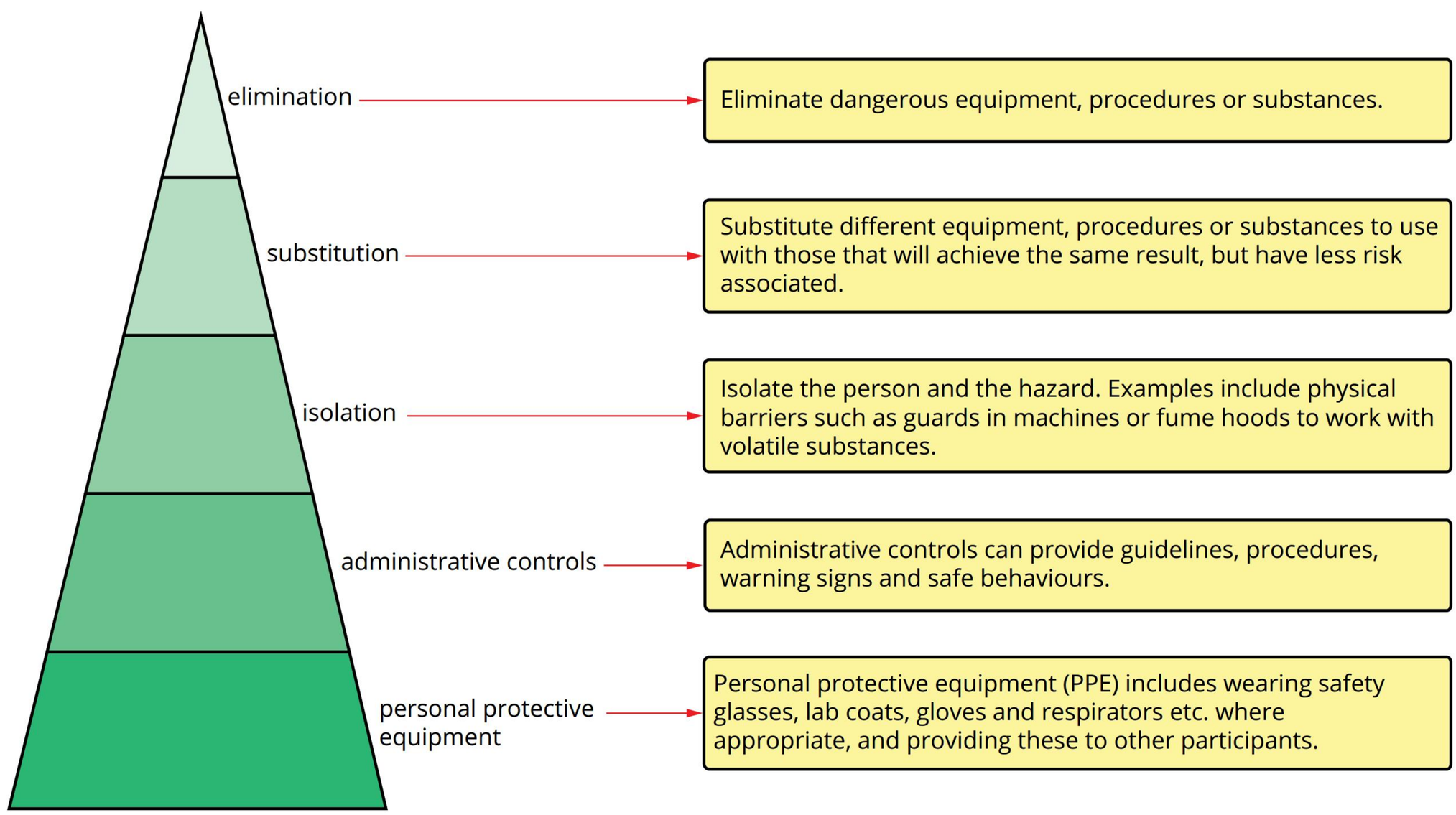


FIGURE 1.11.2 The hierarchy for risk control.

Personal protective equipment

Everyone who works in a laboratory wears items that help keep them safe, such as those shown in Figure 1.11.3. These items are called **personal protective equipment (PPE)** and include:

- safety glasses
- shoes with covered tops
- disposable gloves when handling certain chemicals
- a disposable apron or a lab coat if there is risk of damage to clothing.
- a hair net or tied back hair for using a Bunsen burner.

FIGURE 1.11.3 Examples of PPE shown are protective eye wear, lab coats and gloves.

In workplaces, scientists and many other kinds of workers need to use control measures daily to reduce the risks associated with exposure to hazards. Elimination is the most effective form of control because it removes the hazard. Substitution, isolation and administrative controls reduce the risk. Sometimes, a hazard cannot be removed and the associated risks of a negative outcome occurring cannot be sufficiently reduced. If a risk is still present, even though PPE is the least effective control measure overall, it is the most effective way that an individual can protect themselves from harm.

Environmental and ethical considerations

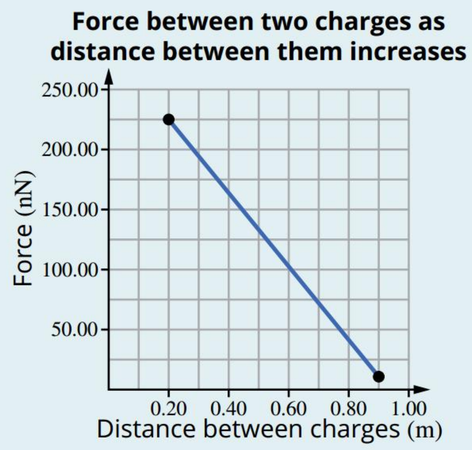
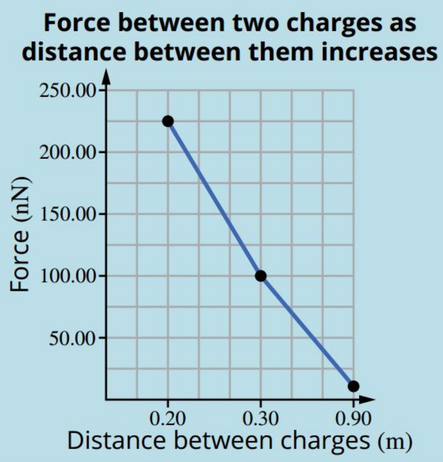
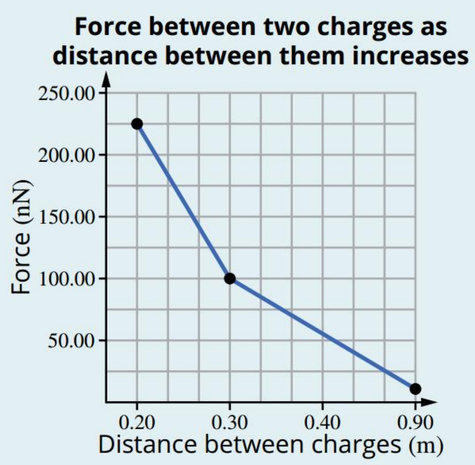
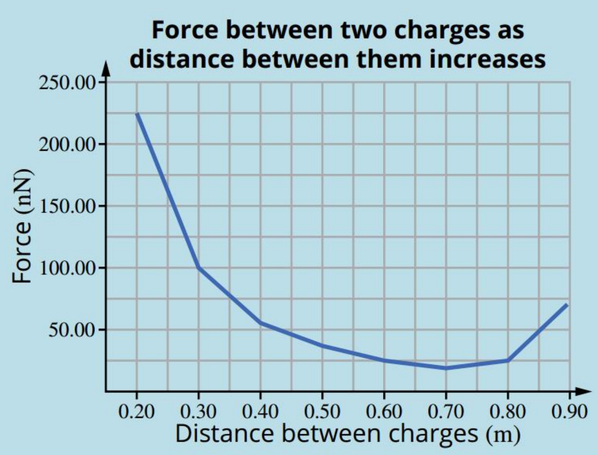
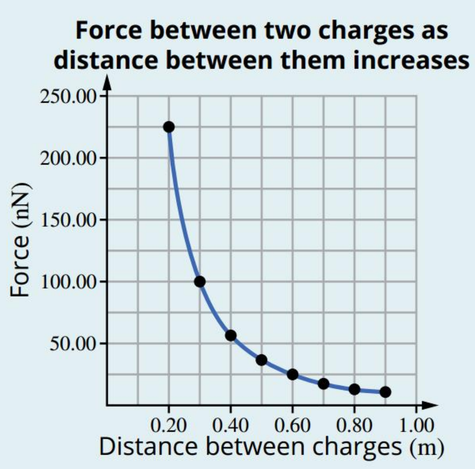
When planning an investigation, identify any relevant environmental and ethical considerations, and evaluate the mitigation of these issues. For example, the metals and acids used in some batteries can have environmental impacts if disposed of improperly.

Ethics is a set of moral principles by which your actions can be judged as right or wrong. Scientists must obtain approval from an ethics committee and follow ethical guidelines relating to animals and humans. School physics investigations generally only have minor ethical issues, if any. However, consider if during the experiment, one party or group benefits over another, or are there real-world connotations of the investigation not accepting of the rights of a community group.

COLLECTION OF SUFFICIENT AND RELEVANT RAW DATA

Enough data needs to be collected to substantiate whether a relationship exists between the dependent and independent variables. For the data to be *relevant*, the investigation must collect values for independent and dependent variables as described in the Research Question. For the data to be *sufficient* means to have appropriate sample size in terms of an appropriate number of replicate trials and an appropriate number of variations of the independent variable. Sample size will impact on the accuracy of the data, the uncertainty within the data collected, and the ability to interpret the data. In general, a minimum of five data points and five measurements per data point (five trials) are needed. This provides a sample size consistent with sufficient and relevant data, and allows for the removal of some outliers without substantially impacting the overall quality of the data. Table 1.11.3 outlines examples of sample size and their effect on the results of an experiment.

TABLE 1.11.3 Examples of sample size and their effect on the results of an experiment

Examples of analysed data	Effect of sample size on analysis
A line graph with two sample points 	With only two individual sample points, this graph suggests an inappropriate linear relationship for the force acting between two charges as the distance between them increases.
Line graph with three sample points and an uneven scale 	The scale on the horizontal axis is not evenly spread, which distorts the shape of the graph. These results suggest an incorrect relationship for the force acting between two charges as the distance between them increases.
Line graph showing limited sample points and an uneven scale 	The chosen number of individual sample points is insufficient, because the true relationship is not fully displayed. The next example of displayed results provides more validity for the relationship.
Line graph based on data that had no replicates 	These results are due to only a single measurement for each individual sample point. In this example, the measurements for distances greater than 0.70 m are incorrect. These results suggest an incorrect relationship between the variables.
Scatter graph with appropriate number and distribution of sample points 	The number of individual sample points here best demonstrates the relationship between the variables. Note that a scatter plot has been used rather than a line graph.

Having determined your sample size, check with your teacher that your protocol and schedule (methodology) are appropriate. You need to be able to perform your experiment independently, in the time available in the school laboratory, and with minimal support from your teachers and school laboratory staff.

It is common for experimentation and testing not to go according to plan even if comprehensive background research has been undertaken. Refinements such as reducing or increasing the sample size may be necessary due to timing issues, change to instrumentation or resource limitation.

If the expected data is not obtained, do not worry. Sometimes a different point of view, such as from a fellow student or a teacher, is all that is needed to find a solution. If the data can be critically and objectively evaluated in your report (limitations of the investigation are identified) the work is worthwhile. Unexpected data provides students with an opportunity to add depth to their experimental report by critically evaluating issues in the experiment. There may be evidence of extraneous variables (not previously recognised) or confounding factors. Evaluation of the methodology based on evidence collected and suggested improvement(s) is a key section of the scientific report.

Record everything. The initial data set in your journal may contain both quantitative (values and measurements) and qualitative (observations) data. Note any difficulties encountered or trials which were conducted slightly differently; perhaps the experiment was conducted over two lessons resulting in a change in room temperature, a new measuring instrument, or a different person determining the readings. This information may be influential in your analysis and evaluation. With justification, a data point can be identified as an anomaly and removed from the data set due to being an outlier. This may be due to a mistake or failure to correctly follow the method (see Data Processing). Nevertheless, all values need to be recorded in the raw data table. Choosing not to record certain measurements or observations is invalid, shows bias and is scientifically fraudulent. Quality scientific analysis processes the raw data as it is and is open to any result.

A workable plan for data collection is for one group member to be responsible for recording. This minimises clutter at the experimental work bench and provides a consistent single data set to share with the group. The recording person should add the measurement uncertainty of each piece of equipment or instrument as a range of data next to the measured value (e.g. measurement ± Δ measurement). Conducting the experiment and collecting data is a group activity, however all subsequent parts of the task (data processing, analysis, evaluating and concluding) are completed individually. Therefore, it is important that the data set is disseminated to the group immediately the experiment finishes.

Electronic data acquisition in schools

Electronic data acquisition takes advantage of highly accurate sensors to collect data directly for processing by a computing device (Figure 1.11.4). There are many sensors, probes and instruments available that can measure a vast variety of phenomena in a single device.

FIGURE 1.11.4 Data acquisition software produces real-time graphs that can be downloaded or printed.

Many smartwatches and apps in phones include digital sensors and **data loggers** (Figure 1.11.5) that can be accessed and used for some class practicals and experiments. The video camera of a phone or tablet is also an excellent means of capturing data, particularly for investigations in kinematics and dynamics.

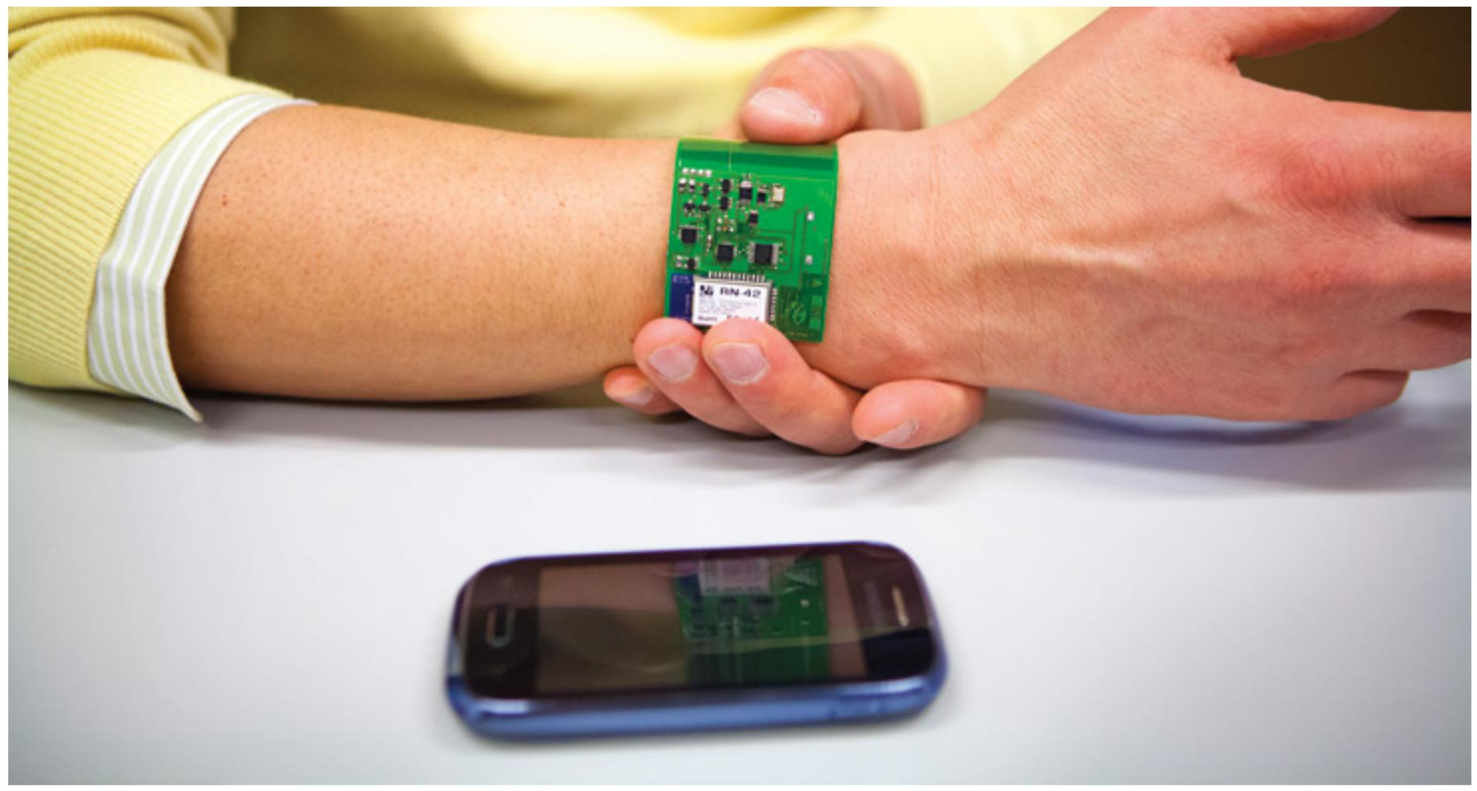


FIGURE 1.11.5 Many smartwatches and phones have digital sensors and in-built data loggers.

Often one of the measurements is time; the user decides what the other measurement (or variable) is by selecting the type of sensor, or probe, to use. Probes can measure temperature, pH, gas pressure, conductivity, concentration of gases in air, or the amounts of pollutants in the environment along with many more phenomena.

Recording is done accurately and can be continuous or manual, and the measurements are saved electronically. The saved measurements can then be accessed via a computer or directly from the tablet screen. The rate at which measurements are recorded is called the sample rate. Data capture rate can be varied from 100 000 times per second through to once an hour, and the duration of recording adjusted to a suitable interval (Figure 1.11.6).

FIGURE 1.11.6 (a) Sensors connected to computing devices such as phones and tablets are readily used in the field. This one is being used to measure the periodic nature in the movement of a playground swing. (b) Many different probes and sensors can attach to a single device, such as in the use of accelerometers and angle sensors to measure the lift of a bar. (c) They can be very precise and measure multiple times per second, such as the frequency and amplitude of air vibrations in sound to record motion. (d) They are usually easy to use and produce results immediately; for example, this sensor measures the temperature of skin on contact.

PUTTING IT ALL TOGETHER

This is the risk management and raw data for the investigation in 1.10 Forming (an investigation into the relationship between pendulum length and period for a simple pendulum as a method of verifying the acceleration due to gravity).

Risk management

TABLE 2 Risk management

Risk	Consequence	Mitigation
Someone could be hit by the bob.	Someone could suffer an injury.	The pendulum will be controlled, and the immediate surrounding area will be cleared before each trial.
Someone could be hit by the ruler.	Someone could suffer an injury.	The ruler will be used with caution and with control.

Results

TABLE 3 Raw data

Length (m, ± 0.001)	Predicted Period, *T* (s)	Period *T* (s, ± 0.05)							
		T1	T2	T3	T4	T5	Average	Absolute Uncertainty	Percentage Uncertainty
0.365	1.2123	1.23	1.21	1.21	1.19	1.21	1.21	0.020	1.65%
0.430	1.3158	1.31	1.31	1.32	1.31	1.35	1.32	0.020	1.52%
0.485	1.3974	1.41	1.43	1.41	1.41	1.39	1.41	0.020	1.42%
0.550	1.4881	1.46	1.49	1.48	1.51	1.51	1.49	0.025	1.68%
0.615	1.5736	1.60	1.58	1.57	1.57	1.58	1.58	0.015	0.95%

No significant outliers (> ±10%) were identified.

1.12 Analysing

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- process data using a range of mathematical calculations
- present sample calculations
- analyse data to prepare graphs and identify trends
- analyse data to identify precision of evidence (using uncertainty) and accuracy of evidence (using percentage error).

PROCESSING THE DATA (SAMPLE CALCULATIONS)

Processing the data in numerous ways (including mathematical techniques and graphing) allows elucidation of relationships between variables. You will analyse trends or patterns in the data, uncertainties and limitations, outliers and results of significance. To prepare your processed data, you should consider which of the following mathematical techniques are suitable in your investigation:

- average (mean)
- measurement uncertainty (absolute measurement uncertainty and percentage measurement uncertainty)
- propagation of measurement uncertainty (addition, subtraction, multiplication, division)
- primary graphs (scatterplots showing raw data)
- secondary graphs (scatterplots showing processed, linearised data with error bars, lines of best, maximum, and minimum fit, and R^2)
- Gradient and intercept analysis
- Uncertainty of the mean and intercept (absolute and percentage)

$$\Delta\bar{x} = \pm\frac{(x_{max} - x_{min})}{2}$$

$$\text{percentage uncertainty (\%)} = \left(\frac{\text{absolute uncertainty}}{\text{measurement}}\right) \times 100\%$$

- Percentage error

$$\text{percentage error (\%)} = \left|\frac{\text{measured value} - \text{true value}}{\text{true value}}\right| \times 100\%$$

These techniques are explained in Part A Working Scientifically and in the science inquiry section of the syllabus.

When you have decided which of these techniques are valid for your investigation, prepare a processed data table and include a sample calculation table which shows a single calculation for each. Remember, there are two types of uncertainty: one associated with the measuring equipment (measurement uncertainty) and one associated with the range of trials (uncertainty of the mean). Both of these values can be expressed as the calculated value (absolute uncertainty) or converted to a percent of the measurement or mean that they describe (percentage uncertainty).

Table 1.12.1 shows an example of raw data, with the processed (linearised) data for comparison shown in Table 1.12.2. The same raw data is presented in Table 3 on page e104.

Results

TABLE 1.12.1 Raw data

Length (m ± 0.001)	Predicted Period, *T* (s)	Period *T* (s, ± 0.05)								
		T1	T2	T3	T4	T5	Average	Absolute Uncertainty	Percentage Uncertainty	Maximum Uncertainty
0.365	1.2123	1.23	1.21	1.21	1.19	1.21	1.21	0.020	1.65%	0.05
0.430	1.3158	1.31	1.31	1.32	1.31	1.35	1.32	0.020	1.52%	0.05
0.485	1.3974	1.41	1.43	1.41	1.41	1.39	1.41	0.020	1.42%	0.05
0.550	1.4881	1.46	1.49	1.48	1.51	1.51	1.49	0.025	1.68%	0.05
0.615	1.5736	1.60	1.58	1.57	1.57	1.58	1.58	0.015	0.95%	0.05

No significant outliers (> ±10%) were identified.

TABLE 1.12.2 Linearised data

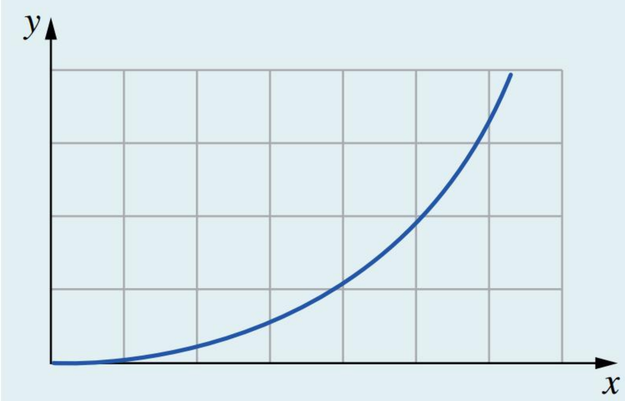
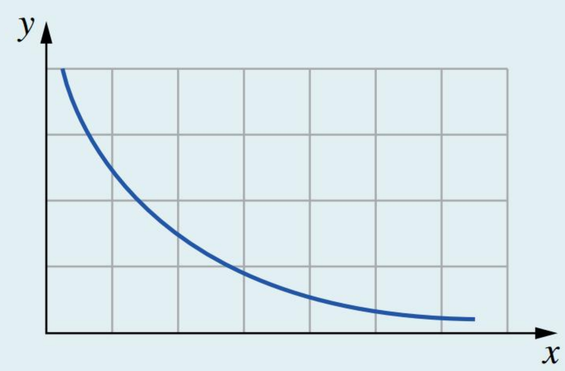
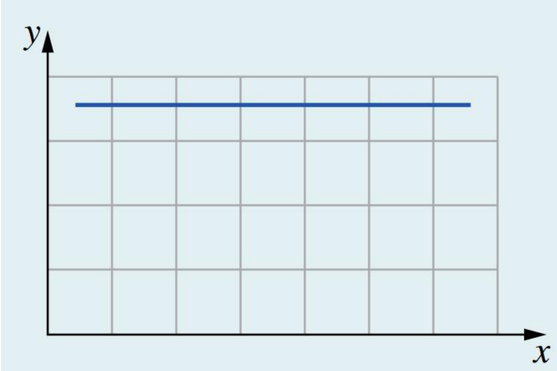
Length (m ± 0.001)	Predicted Period *T* (s)	Period-squared T^2 (s^2)								
		T1	T2	T3	T4	T5	Average	Absolute Uncertainty	Percentage Uncertainty	Propagated Uncertainty
0.365	1.2123	1.51	1.46	1.46	1.42	1.46	1.46	0.048	3.31%	0.06
0.430	1.3158	1.72	1.72	1.74	1.72	1.82	1.74	0.053	3.05%	0.05
0.485	1.3974	1.99	2.04	1.99	1.99	1.93	1.99	0.056	2.84%	0.06
0.550	1.4881	2.13	2.22	2.19	2.28	2.28	2.22	0.074	3.34%	0.07
0.615	1.5736	2.56	2.50	2.46	2.46	2.50	2.50	0.048	1.90%	0.05

When calculations are performed with data values, the uncertainties associated with these values are combined in a process called propagating uncertainties. For example, if a density value is calculated using measured mass and volume, using the relationship density = $\frac{\text{mass}}{\text{volume}}$, then the percentage uncertainty for the measurement of mass (weighing balance) is added to the percentage uncertainty for the measurement of volume (measuring cylinder). This total gives the percentage uncertainty for the density (refer to Part A).

Identifying trends, patterns and relationships

There are several ways to present processed data, depending on its nature, including tables, graphs, flow charts and diagrams. In Physics, this is almost always a scatter plot – a clear visual representation showing a direct or inverse relationship between the dependent variable and the independent variable and if the relationship is linear or not. A spreadsheet program will provide information about the trendline gradient and an R^2 value. By plotting expected values (if known) on the same graph the accuracy of the data is visualised. Several trends which may be identified on your primary graph are shown in Table 1.12.3. Regardless of the type of trend shown on the primary graph, a linearised secondary graph showing lines of best, minimum, and maximum fit should be generated using processed data. See Part A for further information on the linearisation process.

TABLE 1.12.3 Graphs showing different trends and relationships between variables

Variables that change in linear or direct proportion to each other produce a straight, sloping trend line. 	Variables that change exponentially in proportion to each other produce a curved trend line. 
When there is a negative relationship, one variable increases as the other variable decreases. It may be (a) direct or (b) non-linear. 	When there is no relationship between two variables, one variable will not change even if the other changes. 

Plotting error bars and maximum and minimum trendlines on a graph indicates if the averages shown are significantly different. Overlapping error bars indicate that the difference between these two values is not statistically significant. The graph(s) that you have prepared provide evidence of the relationship between the dependent and independent variables; however, you should describe the features of the graph using a succinct statement:

'As (independent variable) increases (dependent variable) increases/decreases.'

It would be useful to follow this with some values from the graph to justify the occurrence of the trend. Further useful analysis could describe the gradient, intercept, R^2 value, similarity/difference to the expected values and whether the error bars overlap or not. Remember, the report has an evaluation section so at this stage it is not necessary to fully explain every aspect of the data. A 'thorough and appropriate identification of trend/patterns/relationships' is what is required here in the Analysis section.

In Physics, it would be appropriate to state the equation from the linearised secondary graph, including uncertainties, in this section. If the chosen experiment is one where the gradient of the secondary graph is meaningful, and contains a relevant proportionality constant, this would be an appropriate place within the report to determine this value. An example of these aspects is shown below.

The experimental linear relationship, including uncertainties was found to be:

$$T^2 = 4.10(\pm 0.74) \times l - 0.02(\pm 0.36)$$

This is consistent with the theoretical relationship of $T^2 \propto l$. The gradient is equal to $\frac{1}{g} \times 4\pi^2$ allowing for an experimental value of g to be determined:

$$4.10 = \frac{1}{g} \times 4\pi^2$$

$$g = 9.63\,\text{m}\,\text{s}^{-2} \pm 18.05\%$$

$$g = 9.63\,\text{m}\,\text{s}^{-2} \pm 1.74$$

The percentage error was determined by comparing the observed and expected values:

$$\text{percentage error (\%)} = \left|\frac{\text{measured value} - \text{true value}}{\text{true value}}\right| \times 100\%$$

$$\text{percentage error (\%)} = \left|\frac{9.63 - 9.81}{9.81}\right| \times 100\%$$

$$= 1.83\%$$

Uncertainty, precision and reliability

In Physics, there is always variation in measurements (the terms precision and uncertainty were explained in Part A). The level of uncertainty is indicated by:

1. using the measurement uncertainty of the instrument(s) or
2. using the range of trials and dividing by 2 (uncertainty of the mean).

Both can be expressed as a percentage of the value they describe, and both give us an indication of the level of random error in the experiment. When identifying and discussing the level of random error, it is most useful to calculate both and relate the analysis to the higher value. Whichever is the larger source of uncertainty is used to generate the error bars on the secondary graph.

Consider these two uncertainty types in an example dataset (Table 1.12.4) which shows the horizontal displacement of a projectile undergoing horizontally projected motion from a given height on. Firstly, the uncertainty due to the precision in the measurement instrument (measurement uncertainty) is half a division of the scale (±0.005), multiplied by two due to using both ends of the instrument (±0.01 m). When expressed as a percentage of the mean, this is 0.049%.

Secondly, the uncertainty of the mean is calculated using:

$$\text{Uncertainty of mean} = \frac{\text{range}}{2}$$

giving a uncertainty of ±0.40 m. When expressed as a percentage of the mean, this is 1.95%. We see that the uncertainty of the mean is greater than the measurement uncertainty and so we can deduce that the precision of the measurement instrument is only slightly contributing to the level of random error in the experiment. There are further factors contributing to the 1.95% uncertainty.

In addition, as the 1.95% relative uncertainty of the mean is quite low, we can state that the data is precise and reliable, and that the level of random error in the experiment is low.

TABLE 1.12.4 Horizontal displacement of a projectile undergoing horizontally projected motion from a given height

Trial	Horizontal displacement of projectile (cm)
1	20.62 ± 0.01
2	20.93 ± 0.01
3	20.13 ± 0.01
4	20.47 ± 0.01
Mean	20.50 ± 0.40

Percentage error, accuracy and limitations of the evidence

The rationale has provided background information that informs the relationship proposed in the research question. This provides your expected trend and, in your analysis, you will state if this trend was obtained. In addition, you may be able to

research expected values for the data set that you have collected, or the gradient/proportionality constant you have obtained. If this is the case, it is expected that you will calculate percentage error values for the data points or gradient/proportionality constant.

Percentage error measures how different your data is to expected values and so will allow you to make a judgement about accuracy and validity. Low percentage error indicates low systematic error in the investigation. By researching expected values you are accessing experimental data from scientific laboratories, or the defined values of proportionality constants, and so we expect that the equipment and methodology in a secondary school laboratory is unlikely to accurately replicate these values. Percentage error is likely to be quite high given these limitations. Nevertheless, if a percentage error value is unreasonably high, such as 50%, you can identify a lack of accuracy and the investigation is lacking validity; state this as a limitation.

Again, when identifying these issues as part of trends, patterns and relationships, resist the temptation to explain and suggest reasons for these results because this discussion is more relevant to the concluding and evaluation sections.

PUTTING IT ALL TOGETHER

The sample experiment report below follows the ISMG criteria and may be used as a reference tool.

These are some sample calculations and analysis for the investigation in 1.10 Forming (an investigation into the relationship between pendulum length and period for a simple pendulum as a method of verifying the acceleration due to gravity).

Processed data and sample calculations

TABLE 4 Samples of the calculations used to process the data and associated uncertainties management

Calculation	Working
length measurement uncertainty	0.005 per end, with two ends measured = ±0.01 m
period measurement uncertainty	Reported accuracy of 25 milliseconds (Vernier, 2019), with two measurements required per time interval = ±0.05 s
theoretical period	$T = 2\pi\sqrt{\frac{l}{g}}$ $= 2\pi\sqrt{\frac{0.365}{9.81}}$ $= 1.21\,\text{s}$
average (mean)	$\text{average (mean)} = \frac{T1+T2+T3+T4+T5}{5}$ $= \frac{1.23+1.21+1.21+1.19+1.21}{5}$ $= 1.21\,\text{s}$
trial uncertainty	$\text{uncertainty} = \pm\frac{\text{upper value} - \text{lowest value}}{2}$ $= \frac{1.23-1.19}{2}$ $= \pm 0.02$

Calculation	Working
percentage uncertainty	$\text{percentage uncertainty (\%)} = \left(\frac{\text{absolute uncertainty}}{\text{measurement}}\right) \times 100\% = \frac{0.05}{1.21} \times 100\% = 4.13\%$
period squared	$T^2 = 1.21^2 = 1.46\,\text{s}^2$
period-squared propagated uncertainty	$1.46 \times \frac{2 \times 4.12\%}{100} = \pm 0.12$
gradient uncertainty	$\text{uncertainty} = \pm\frac{\text{upper value} - \text{lowest value}}{2} = \frac{4.92 - 3.45}{2} = \pm 0.74$
gradient percentage uncertainty	$\frac{0.74}{4.10} \times 100 = 18.05\%$
intercept uncertainty	$\text{uncertainty} = \pm\frac{\text{upper value} - \text{lowest value}}{2} = \frac{0.28 - (-0.43)}{2} = \pm 0.36$

Analysis

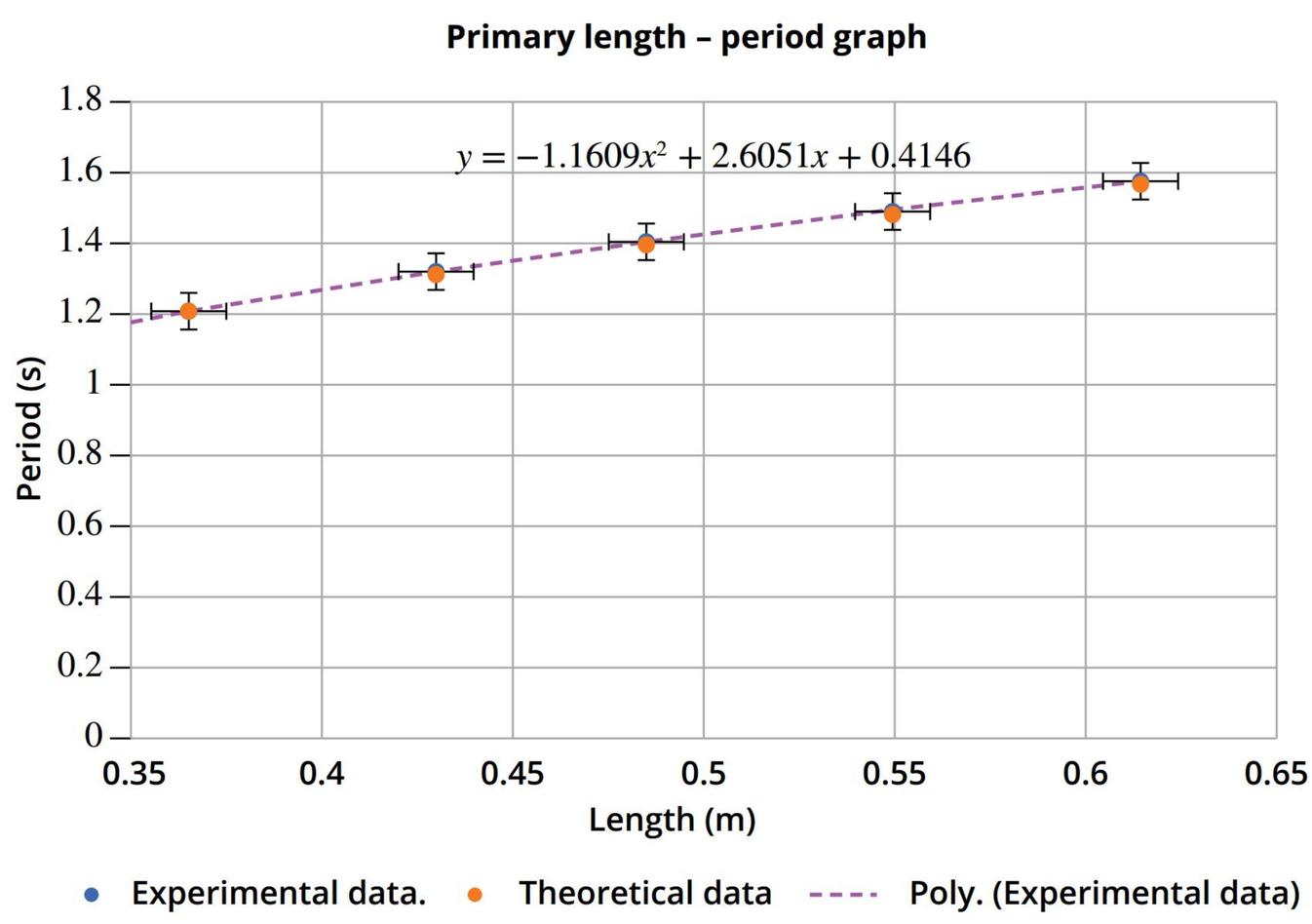


FIGURE 2 Primary graph showing experimental primary data and theoretical values

As the length of the string increases, the length of the period increases on a parabolic curve as expected, as the original relationship used to graph this includes a surd. According to Figure 2, a string of length 0.365 m produced a period time of 1.21 s, furthermore when the length of the string increased to 0.483 m, the period length also increased to 1.32 s and the rest of the data follows this trend. The dependent variable data has an uncertainty of ±0.05 as the measurement uncertainty was greater than the trial uncertainty. The theoretical and experimental data is very similar, though a small difference can be seen indicating there is some limiting factor effecting the results. To further verify the relationship, the relationship was linearised and a secondary graph was generated (Figure 3).

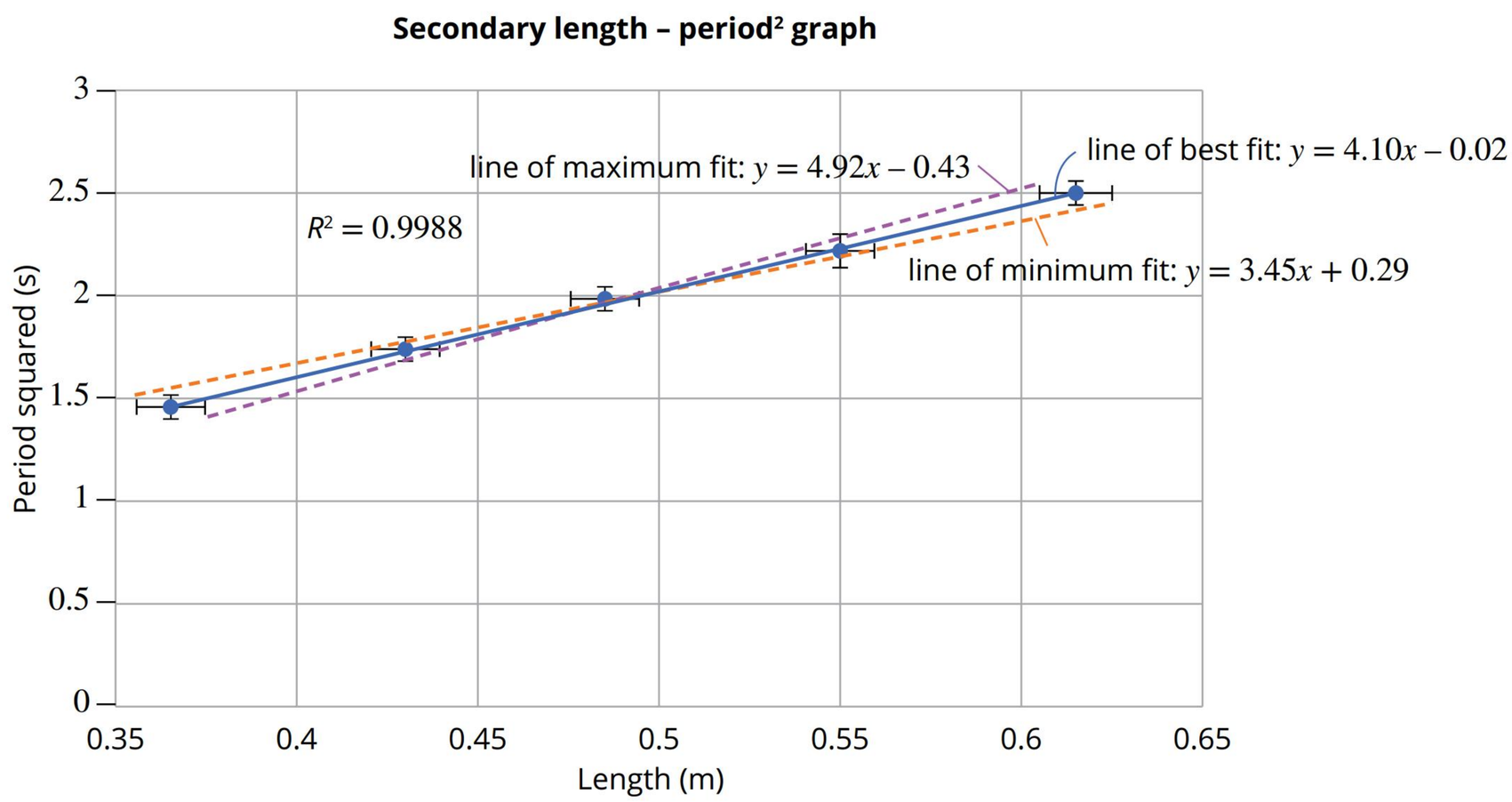


FIGURE 3 Secondary graph showing the linearised relationship, including lines of maximum, minimum, and best fit

The experimental linear relationship, including uncertainties was found to be:

$$T^2 = 4.10(\pm 0.74) \times l - 0.02(\pm 0.36)$$

This is consistent with the theoretical relationship of $T^2 \propto l$. The gradient is equal to $\frac{1}{g} \times 4\pi^2$ allowing for an experimental value of g to be determined:

$$4.10 = \frac{1}{g} \times 4\pi^2$$

$$g = 9.63\,\text{ms}^{-2} \pm 18.05\%$$

$$g = 9.63\,\text{ms}^{-2} \pm 1.74$$

The percentage error was determined by comparing the observed and expected values:

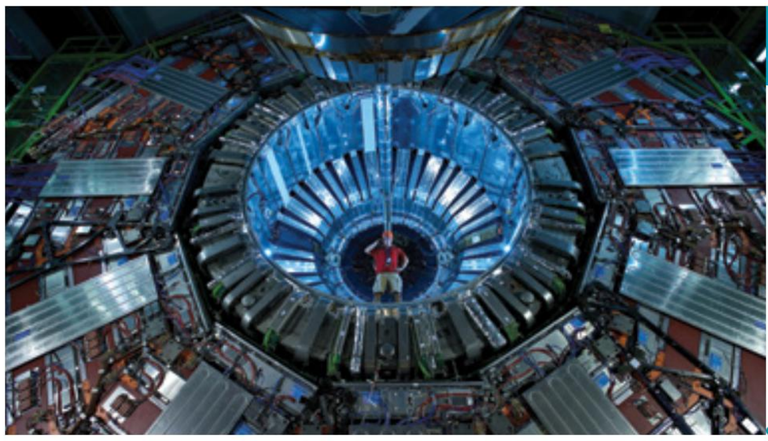
$$\text{percentage error (\%)} = \left|\frac{\text{measured value} - \text{true value}}{\text{true value}}\right| \times 100\%$$

$$\text{percentage error (\%)} = \left|\frac{9.63 - 9.81}{9.81}\right| \times 100\%$$

$$= 1.83\%$$

This error is considerably smaller than the uncertainty of the gradient which supports the accuracy of the experiment, and the appropriateness of the theoretical relationship between period and length. This was further supported by the correlation coefficient R^2 having a value greater than 0.99, and the *y*-intercept being essentially zero, as expected from the theoretical relationship.

1.13 Interpreting and evaluating



BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- formulate a conclusion linked to the research question using interpretation of evidence
- justify your conclusion
- evaluate reliability and validity, and justify your arguments with evidence
- suggest improvements and extensions.

Interpreting and evaluating requires a justified conclusion, justified discussion of the quality of the experimental process and suggestions for improvements and extensions derived on the analysis of the evidence.

JUSTIFIED CONCLUSION LINKED TO THE RESEARCH QUESTION

While you have already described the trend observed in the data (Analysis) it is important, in the conclusion, to extend this idea further to relate specifically to the research question. In an objective and clear manner, state the observed relationship between the dependent and independent variables using the terminology of the research question. Consider

- was the research question supported?
- has the research question been fully answered? If not, identify why not?

Table 1.13.1 shows examples of concluding statements.

TABLE 1.13.1 Strong and weak conclusions to a research question

Research question: How does the refractive index affect the angle of the refracted ray if the angle of incidence remains constant?	
Strong conclusion	**Weak conclusion**
Analysis of the results on the effect of an increase in refractive index showed an inverse linear relationship in which the sine of the angle of the refracted ray decreased from 0.57 to 0.44 as the refractive index increased from 1.3 to 1.6. These results support the expected theoretical relationship from Snell's law $n_1 \sin(\theta_1) = n_2 \sin(\theta_2)$ where an increase in n_2 requires a proportional decrease in $\sin(\theta_2)$, given $n_1 \sin(\theta_1)$ remains constant.	The results show that increasing the refractive index caused the refracted angle to decrease.

There are several ways to justify the conclusion including but not limited to:

1. describing the physics concepts (scientific understanding and theory) that explains the observed relationship. Does the identified experimental relationship match the expected theoretical relationship? Is the expected theoretical value for the gradient/proportionality constant within the error bars of the experimentally determined value?
2. describing the evidence that led to the data trend. State values that indicate the strength of the relationship between the experimental variables (data, observations or results) including information gained from the errors bars on the graph, the R^2 value(s), the gradient and/or intercept uncertainty, and the percentage error. Refer to your tables/graphs to cite evidence.
3. comparing your finding to secondary data. This can be sourced from journal articles or other reliable sources that are directly connected to the experiment. Explain if the results support your observations. You should report that your

results are consistent with the findings. Otherwise, it is essential that you reflect on the contrasting results and identify or suggest possible explanations why the results differ. This could be due to differences in the measurement technique or other factors such as the control or measured variables. It might also help you identify possible sources of error within your investigation.

In circumstances where a clear trend is not discernible, you can interpret what the results mean. Interpretations are made when limitations exist related to the methodology employed, the sample size, the instruments used, the variables controlled, and the raw data measured. Interpretations are not meant to provide answers and comprehensive explanations, only plausible causes of the limitations which may warrant further investigation.

In the conclusion, it is appropriate to briefly describe evidence relating to the quality of experimentation and any key limitations. You should address both reliability and validity (as described by % uncertainty and % error, respectively). Describe which of these was high/low and what this indicates about reliability and validity. Resist the temptation to explain these further as this is more usefully done in the Evaluation.

The conclusion is sometimes positioned after the analysis and sometimes at the end of the report. Its placement in your report will need to make sense to you and maintain the flow of ideas.

Option 1: planning → data collection and analysis → conclusion → evaluation

Option 2: planning → data collection and analysis → evaluation → conclusion

JUSTIFIED DISCUSSION OF RELIABILITY AND VALIDITY

Your analysis and conclusion have identified the trend in the data but also identified two other key aspects of the data – reliability and validity. A statement of these has also been made in the conclusion. The verb in analysis is 'identify' but here (in Interpreting and Evaluating) the cognition is 'discuss'. This means that you must explain statements made in the analysis related to % uncertainty (reliability) and % error (validity). In your discussion consider:

- are these low or high?
- what is the effect of these on the usefulness of the data to answer the research question? What could have caused excessive uncertainty and random error?
- what could have caused excessive systematic error?
- what factors could affect the validity, accuracy, precision and reliability of data?

As you consider this discussion, remember that your data processing has provided extensive evidence – not just the independent-dependent variable relationship but also measurement uncertainty, uncertainty of the mean, gradient/proportionality constant, intercepts, and percentage error. Use these values to add depth to your discussion and use evidence rather than methodology to describe and discuss uncertainty and limitations in the investigation. For example, if you have calculated the percentage uncertainty associated with the measurement instrument (say, a measuring cylinder) to be 0.24% then suggesting that the lack of precision of this equipment is the cause of a percentage error of 40% is not reasonable.

A second example of the use of evidence relates to percentage error. If you have calculated the percentage error and have found that it increases throughout the experiment, your reasoning should relate to why this factor has increased. An example of this could be the components of an electrical circuit increasing in temperature the more the circuit is used. As a result, we expect the systematic error to increase during the experiment, and so percentage error should increase as well. Coverage of the impact of systematic and random errors on the data and results should be evident in your analysis for the characteristic of 'justified discussion of validity' to be met.

As you discuss factors affecting the quality of the data, remember the definitions of random and systematic error, and describe the factor in terms of one of these. Is the factor expected to always produce a change in the same direction (systematic

error, low validity)? Or will the factor produce a more random effect where the value is sometimes higher and sometimes lower (random error, low reliability)? Look carefully at the evidence in your data for each of these. Refresh your understanding of random and systematic error using Figure 1.13.1.

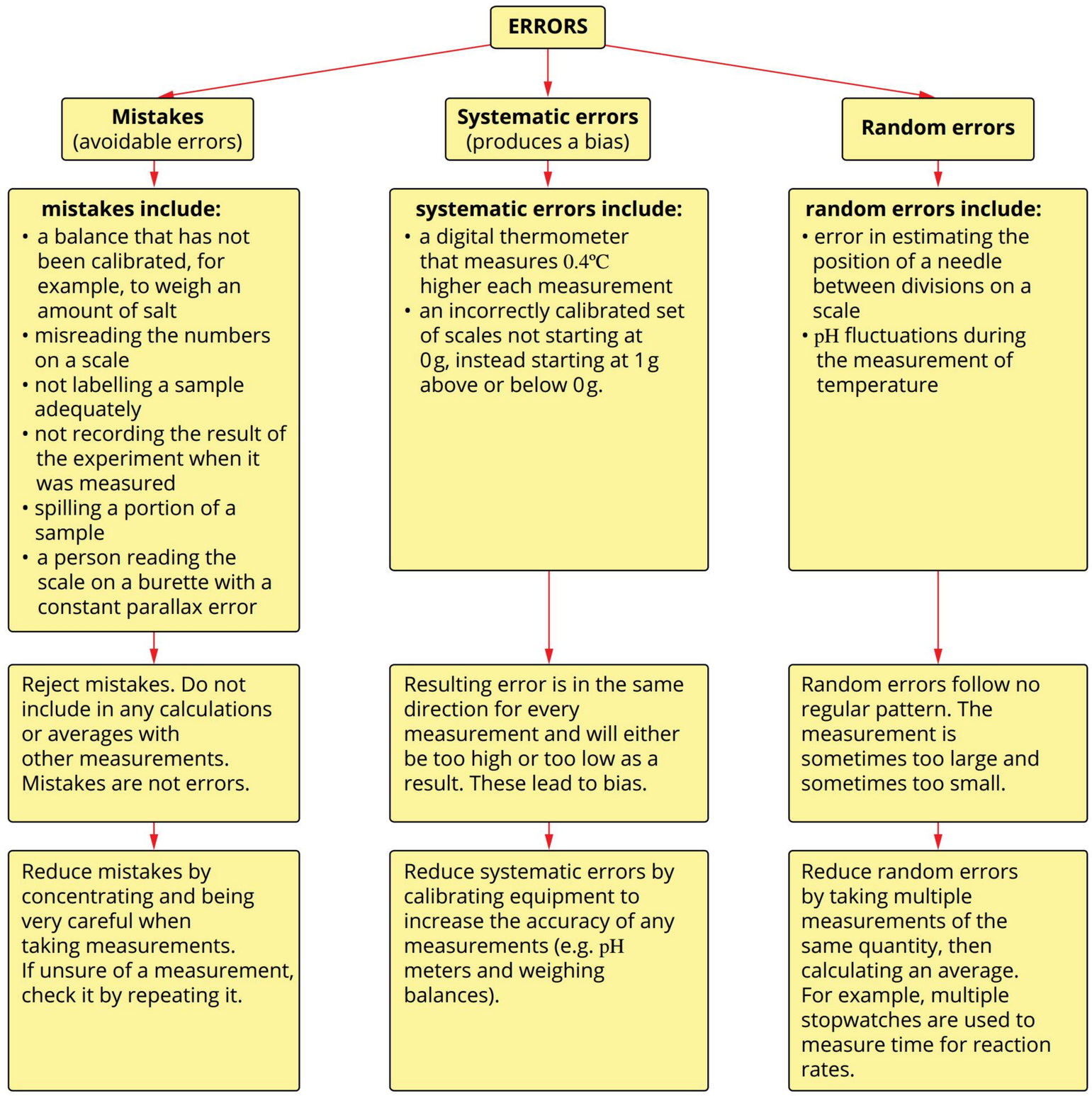


FIGURE 1.13.1 Types of errors that can be made in an experiment

One form of systematic error is bias in sampling or measurements. Bias can result from poor definitions, incorrect assumptions, misunderstandings between group members and failure to use equipment correctly. Some biases cannot be eliminated but should at least be addressed in the discussion.

IDENTIFY IMPROVEMENTS AND EXTENSIONS

Once any limitations or problems in the methodology have been identified, recommend improvements for how the investigation could be conducted if repeated. Some guiding questions are:

- has my research question been fully answered and what evidence is further required to answer it?
- what improvements can be made to aspects of the investigation identified as limitations?
- what changes to the materials or method would address the lack of reliability or validity of the data?

Questions to consider when suggesting extensions to this student experiment could include

- do the findings lead to further questions?
- can the findings be extended to another situation?
- what extensions can be investigated for a related scientific idea?

In the modifications section, you provided a reason for each change that you made to the original experiment. In a similar way, provide a reason for each improvement and extension. In order to demonstrate that the extensions are logically derived from the analysis of the evidence, you need to provide a reason for each extension and how it relates to the evidence. Similarly, how the suggested improvements would have addressed or overcome the limitations that were identified earlier. Statements such as 'test more substances' or 'complete more trials' do not match a high-level response ('logically derived' ISMG descriptor) and will better match lower descriptors ('related' or 'ineffective').

The syllabus descriptor states 'logically derived' and so it is important to limit your suggestions for improvements and extensions to experimental issues that have already been identified (in analysis and evaluation). Conversely, if you have described a key limitation of the experiment related to high levels of random or systematic error, you should describe improvement(s) for this issue.

PUTTING IT ALL TOGETHER

The sample experiment report below follows the ISMG criteria and may be used as a reference tool for interpreting and evaluating.

This is a conclusion and evaluation of the investigation in 1.10 Forming (an investigation into the relationship between pendulum length and period for a simple pendulum as a method of verifying the acceleration due to gravity).

Conclusion and Evaluation

The experimental percentage error of 1.83% was a significant improvement on the original experiment, suggesting the modifications did indeed improve reliability. The presence of the expected value of $9.81\,m\,s^{-2}$ within the experimental uncertainty of $9.63\,m\,s^{-2} \pm 1.74$ suggests the experiment was valid. Regardless, the experiment was still inaccurate, as the experimental value of $9.63\,m\,s^{-2}$ was lower than the theoretical value. Conversely, precision was extremely high, with the absolute uncertainty being lower than the measurement uncertainty for the data trials. This could suggest the presence of random error, though the R^2 value being greater than 0.99 suggests this is unlikely to be the case. Additionally, the negligible *y*-intercept of –0.02 does not suggest the presence of a systematic error.

The uncertainty in the independent variable contributed more to the overall uncertainty than the dependent variable. This is because the photogates are very precise (Vernier reports a maximum uncertainty of 25 ms) and automatic, removing random human error. However, the length of the pendulum was still measured manually using a meter ruler, and introduced a limitation in the form of measurement uncertainty at both ends of the tape measure. This measurement was taken in the air after the pendulum had been mounted to remove the random error which could be introduced to the length if it was measured before being mounted in the pendulum. This does however introduce the possibility of random errors if the ruler and string were out of alignment due to being held unsteadily in the air without any sort of clamp or guide to read the value accurately. It is possible this resulted in the measurement error being higher than the values reported and may represent a significant limitation (see Table 5).

TABLE 5 Improvements

Improvements	Justification
Replace the ruler with a more precise device such as a laser measuring device.	The ruler was the main source of measurement uncertainty. Implementing this modification will improve precision and increase reliability.
Fix the ruler to the table to ensure vertical alignment between pendulum and ruler.	This would reduce the uncertainty when reading the value off the ruler and increase accuracy of the measured length of the string.
Measure the angle of the string more closely rather than estimating.	This improves validity as ensuring the angle of the string is not be larger than 15° reduces other forces on the motion of the pendulum

The lower experimental value of g suggests the presence of a force opposing the motion of the pendulum. It is unlikely this is in the form of air resistance on the bob as the modifications made to the experiment were specifically chosen to limit this. Redirecting the experiment from freefall to a pendulum did however introduce a string. The ideal model of the simple pendulum uses a massless frictionless string. The presence of air resistance on the string, plus frictional forces at the pivot point of the pendulum are likely sources of these forces opposing the motion of the pendulum and are excellent candidates for further experimentation (see Table 6).

The motion of a pendulum should be independent of angle, especially if the angle is kept beneath 15 degrees to limit other forces on the bob (The Physics Classroom, 2023). Admittedly, this meant we did not measure the angle of the string but just estimated it each time. If this estimation was poor, additional forces may have been present which would contribute to random error. Furthermore, a difference in predicted gravity could be due to the location of the experiment; gravitational acceleration is not the same globally as detailed in the rationale. While this may have had some impact, it is unlikely to be as low as $9.63\,\mathrm{m\,s^{-2}}$.

TABLE 6 Extensions

Extensions	Justification
Investigate the relationship between period and angle.	When the angle is greater than 15°, the formula becomes much more complex as more forces are acting on it. This would allow for a greater understanding of the relationship between these variables and would confirm if this contributed to inaccuracy in this experiment.
Investigate the use of different types of string	This would provide evidence for the impact of the motion of the string on the motion of the bob and would allow us to determine if forces on the string contributed to the lower experimental value for gravity.

Conclusion

From the data collected, a conclusive answer for the research question has been determined. The results lead to the conclusion that increasing the length of the string will increase the square of the period. The relationship found within the experiment was:

$$T^2 = 4.10(\pm 0.74) \times l - 0.02(\pm 0.36)$$

This supports the theoretical proportionality of $T^2 \propto l$. The results were deemed to be reliable as despite a percentage uncertainty in the gradient of 18.05%, the percentage error was only 1.83% and the R^2 value was greater than 0.99 suggesting limited influence of random error. The presence of the expected value of $9.81\,\mathrm{m\,s^{-2}}$ within the experimental uncertainty of $9.63\,\mathrm{m\,s^{-2}} \pm 1.74$ suggests the experiment was valid. The inaccuracy of the experimental value, particularly with the value being lower than expected, suggests the presence of additional forces on the pendulum providing an avenue for further research to investigate the impact of these limitations.

References

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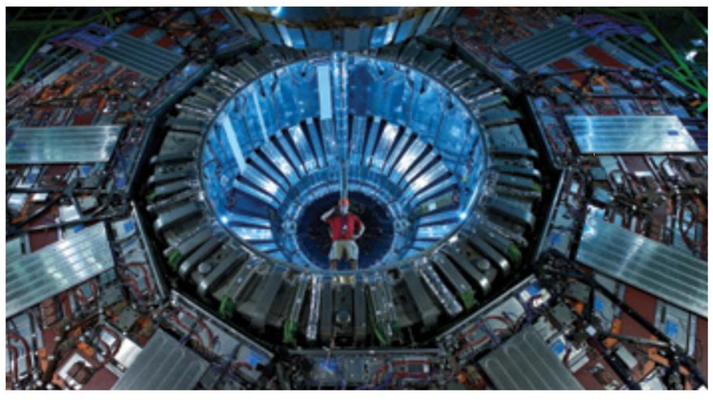
1.14 Syllabus requirements



The research investigation assessment requires students to investigate a claim, provided by their teacher, by drawing on secondary evidence from scientific texts. Students will draw on research to analyse, interpret and evaluate the evidence to reach a justifiable conclusion about the research question. The task requires students to locate and use information beyond the scope of their knowledge and data they have been given.

The Queensland Physics General Syllabus states that students must work individually to develop and investigate their own research question.

The research investigation constitutes 20% of the total subject score and may be presented in:

- written form of up to 2000 words, or
- multimodal form using at least two modes delivered simultaneously and up to 11 minutes.

INSTRUMENT-SPECIFIC MARKING GUIDE

As with the Student experiment, responses are assessed against an instrument-specific marking guide (ISMG). In developing the research report, it is important to keep in mind the assessment objectives, particularly the characteristics that are described in the performance level descriptors.

- The ISMG has four criteria:
  - Forming and finding
  - Analysing
  - Interpreting
  - Evaluating

Each criterion has performance levels, against which the qualities of the response are assessed.

A performance level is comprised of a performance level descriptor and mark (or range of marks).

The performance level descriptor describes the characteristics that are demonstrated by a response of that quality.

Each stage of the development of the research investigation will be discussed and aligned with the relevant ISMG criteria, and elaborations for the highest performances.

The ISMG criteria and elaborations of each are shown in Table 1.14.1, for the highest performances.

TABLE 1.14.1 Alignment of syllabus criteria, objectives, descriptors and marks with the modules of Part B

Criteria	Assessment objectives	Instrument specific marking guide (ISMG) descriptors – Criteria are demonstrated by:	Marks	Module
Forming and finding	1 Describe ideas and findings about special relativity, quantum theory or the Standard Model. 6 Investigate phenomena associated with special relativity, quantum theory or the Standard Model through research.	• a considered rationale identifying clear development of the research question from the claim • a specific and relevant research question • selection of sufficient and relevant resources • appropriate use of genre conventions • acknowledgement of sources of information through appropriate use of referencing conventions	5	1.15 1.8
Analysing	3 Analyse research data about special relativity, quantum theory or the Standard Model.	• the identification of sufficient and relevant evidence • thorough identification of relevant trends/patterns/relationships in evidence • thorough and appropriate identification of limitations of evidence	5	1.16
Interpreting	1 Describe ideas and findings about special relativity, quantum theory or the Standard Model. 4 Interpret research evidence about special relativity, quantum theory or the Standard Model.	• justified scientific argument/s • justified conclusion linked to the research question • fluent and concise use of scientific language/representations	5	1.17 1.8
Evaluating	5 Evaluate research processes, claims and conclusions about special relativity, quantum theory or the Standard Model.	• justified discussion of the quality of evidence • extrapolation of credible findings of the research to the claim • suggested improvements and extensions to the investigation that are considered relevant to the claim	5	1.18
Total			20	

The final report for the student experiment may be organised under the criteria headings in the instrument-specific marking guide (ISMG): forming, finding, analysing and interpreting, and evaluating. However, this is not mandated, and you may elect to organise your report in a different but logical order using alternate headings.

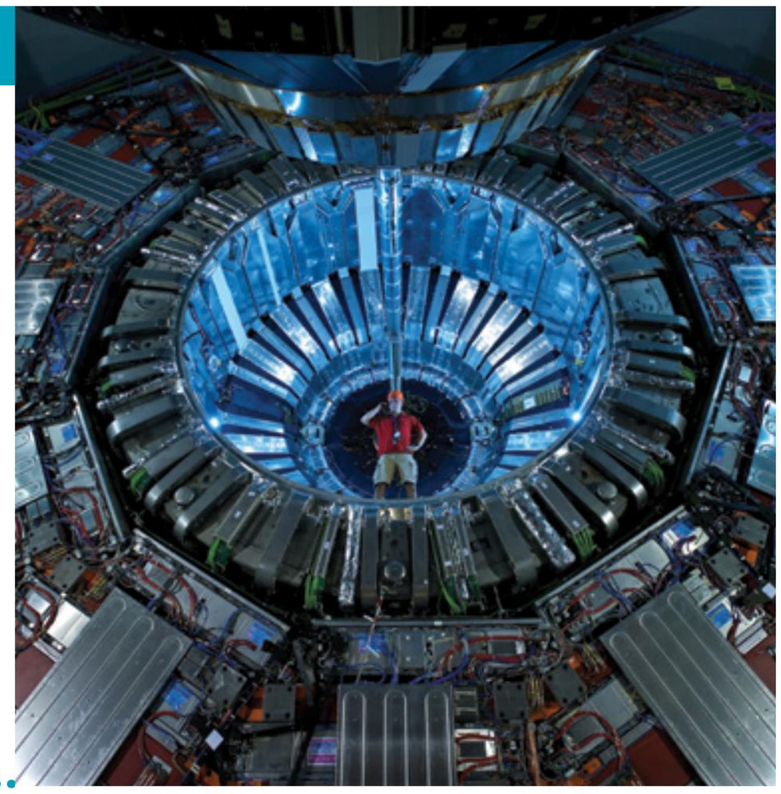
Note that items such as title or contents pages, the abstract, appendixes, bibliography or reference list, and in-text references are not included in the word count. The contents of the appendix are not used for determining levels of achievement.

The research question should specifically address one of the concepts associated with the claim. Commence by identifying a claim and developing your own research question based on that claim. Since this assessment relies heavily on access to research, students need to be able to easily find sources relevant to the research question. Throughout the process be mindful that scientific language and representations are used. (Refer to Module 1.8).

1.15 Forming and finding

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- understand and select a claim
- classify elements of the claim
- unpack the elements to identify variables, terms and concepts related to the claim
- plan research and locate sources relevant to the claim
- distinguish between primary and secondary sources
- locate a range of primary and secondary sources
- use a scientific journal to record the information in the sources
- refine the concepts to develop an investigable research question
- understand the criteria against which the research investigation will be assessed.



The ISMG for the Forming and finding criterion is assessed in relation to the development of the research question from the claim and the communication of the findings of the investigation through a scientific report.

There are three aspects to the Forming and finding criterion.

To achieve the highest mark (5) in the Forming and finding criterion you need to create a specific research question. One way to do this is to clearly link to the subject matter in a way that identifies measurable independent and dependent variables, as well as any relevant controlled variables. Then you need to construct a rationale that clearly outlines how the research question is developed from the original claim. A research rationale outlines the reason to conduct research on your chosen claim, i.e. it is the justification for the investigation. This is achieved by conducting a thorough literature review to understand what is already known in the chosen topic and to identify the concepts from Unit 4 that are related to the topic. Students who explain concepts outside the syllabus in their Rationale struggle to stay within the word limit.

Finally, the structure and style of the report, quality of sources and use of referencing are assessed.

UNDERSTANDING THE NATURE OF A CLAIM

A **claim** is a statement that a phenomena is true, without evidence to support it. The claim can be a sentence, statement within a sentence, title of an article, quote or anything published in any form. The claim should be in isolation from any justification using data, research, evidence or reasoning from known information to support it. The claim is a broad statement that can encompasses a range of related topics and relationships.

SELECTING A CLAIM

If you are provided with a choice of claims, you should ask yourself the following questions about the claims.

Which claims:

- interest me or are most relevant to me?
- will have secondary evidence available to me?
- are easy to break down and link to the subject matter in the unit?
- are broad enough to allow me to undertake a unique investigation?

The answers to these questions will help you decide on the most appropriate claim for you.

To develop the research question from a claim students must analyse, understand and identify one or more of the following:

- known scientific concepts
- variables
- measurable terms
- ideas related to concepts
- a term that is stated to influence another.

Record the information you collect, your thoughts and analysis in a hard copy or electronic scientific journal. When you write the report, this information will be useful in writing the rationale that documents how the research question was developed from the claim. Write down all the elements found in the claim and try to categorise them using the list above. Each element within the claim may suit more than one category. Table 1.15.1 outlines two examples of analysing and categorising elements of a claim.

TABLE 1.15.1 Two examples of analysing and classifying elements of a claim

Example Claim 1: Cold fusion could provide a limitless supply of energy to the world		
Elements	**Classifying elements of the claim**	**Unpacking the elements**
Nuclear fusion	known scientific concepts	source of energy created when smaller nuclei collide and join to make a heavier nucleus
	ideas related to concepts	limited success implementing controlled artificial fusion
Energy production	measurable terms variables	produces energy from matter via $\Delta E = \Delta mc^2$
	ideas related to concepts measurable terms	utilisation of the energy within the grid
	ideas related to concepts measurable terms	efficiency of the energy source: energy required compared to energy produced
Define the term 'limitless'	a term that is stated to influence another. measurable terms	abundance of fuel
	a term that is stated to influence another. measurable terms	amount of waste generated
Explain the significance of 'cold' in this context	known scientific concepts measurable terms	fusion requires high temperature and pressure to start and sustain the atoms must have enough energy to overcome the electrostatic repulsion of the protons in their nuclei achieving fusion at low temperature has not yet been achieved
	known scientific concepts variables	Heat engines require a heat source and a cold sink

Example Claim 2: Photons are a better source of fuel than atoms		
Elements	**Classifying elements of the claim**	**Unpacking the elements**
Photons	known scientific concepts	quantised packets of energy
	ideas related to concepts	does not require a medium
Fuel	ideas related to concepts	mechanism of energy production
	ideas related to concepts measurable terms	abundance and ease of utilisation
Define the term 'better'.	a term that is stated to influence another measurable terms	efficiency
	a term that is stated to influence another ideas related to concepts	photons are massless

Elements	Classifying elements of the claim	Unpacking the elements
Applications	known scientific concepts	propulsion – solar sails
	known scientific concepts	generation – solar cells
	known scientific concepts	storage – batteries

LOCATING SOURCES

It is important to recognise that this is not a university quality report as students do not have the time, access or understanding to analyse the information provided in scientific research journals. In addition, the research investigation is limited to 2000 words so does not allow for the depth of investigation in a research journal.

When gathering scientific evidence for the research investigation, source it from reputable publications including:

- scientific journals, research papers and scientific reviews
- scientific articles written by organisations who apply scientific research to their industry
- commercial articles such as science magazines, newspapers and also websites.

The research investigation must include a reference list of sufficient and relevant sources. *Sufficient* means 'enough or adequate for the purpose', and *relevant* as 'bearing upon or connected with the matter in hand; to the purpose; pertinent; applicable and pertinent; has direct bearing on'. Figure 1.15.1 points out the features of sources deemed *sufficient* and *relevant*.

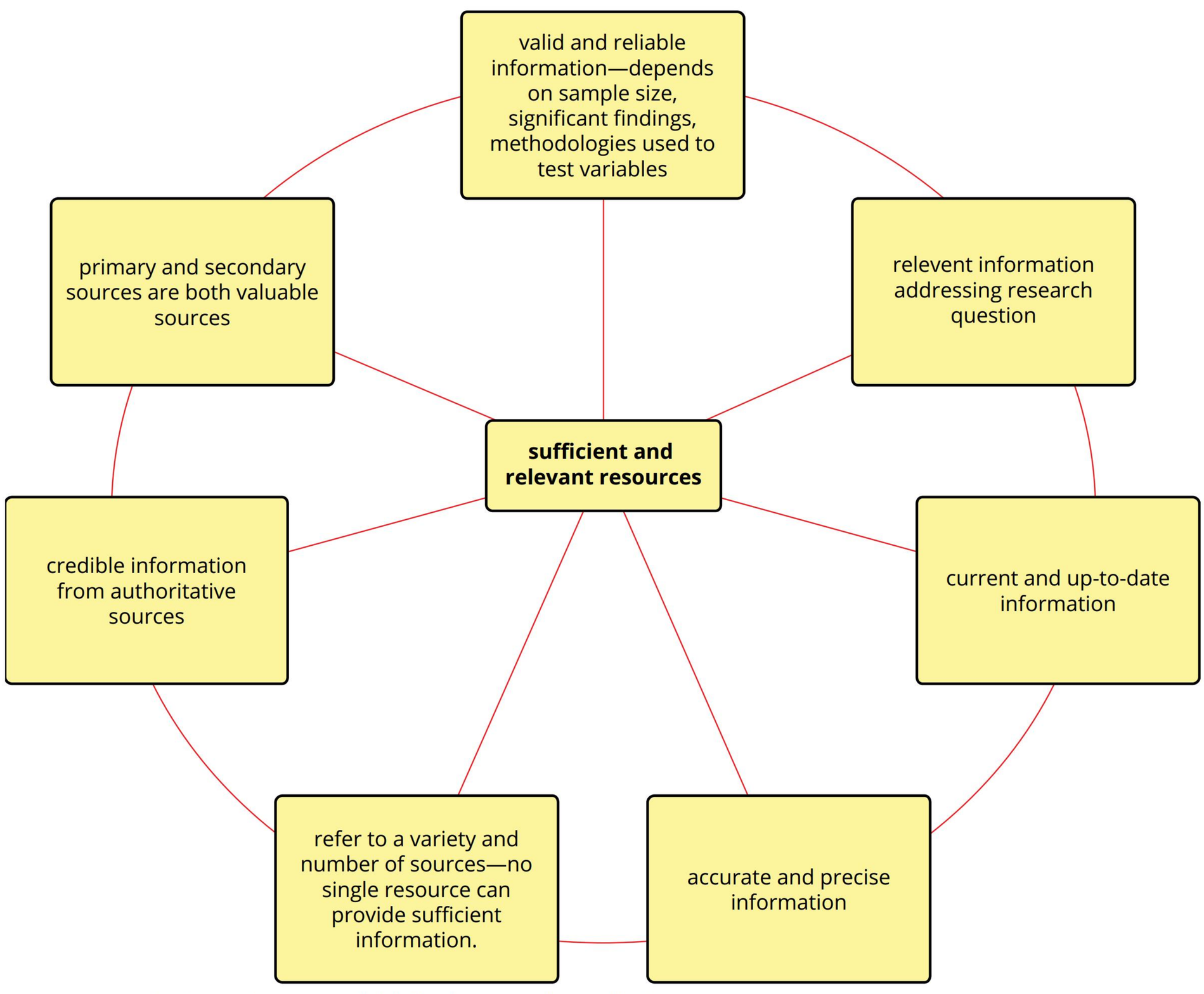


FIGURE 1.15.1 Features of sources suitable for the research investigation

A good place to start research is to look for interesting sites and textbooks to identify relevant keywords and concepts rather than immediately searching for complex research articles. This could include videos, general scientific articles and even Wikipedia to gain a general understanding of the topic.

Access available open-access sources, some of which can be identified using educational, government or industry websites, with suffixes including .edu .gov or .org. There are academic search engines such Google Scholar and Semantic Scholar. Be aware that both of these use AI to search for your requested articles and that may involve some bias. However, this does not mean the article itself is AI-generated.

Where necessary, you can often freely access scientific journals through academic networks, such as ResearchGate and Academic.edu. If the article has not already been published, you can request a copy of the article from the author or ask them a question. You school librarian can help here.

When accessing the sources start with the title, which should include some of the keywords related to the concept. As you refine the focus of your investigation use the evidence to refine the claim and develop the rationale. Your search will narrow and lead to data tables, graphs, images and abstracts. If the abstract is useful, download the article or request a copy of it. Look at the images and conclusion. These may be more useful than the text of the article.

Remember to document the sources and summarise the information contained in your journal to facilitate the writing of the report and generate a reference list. Some sources provide help with the citation of scientific articles.

A useful way to collate the evidence is in a table with headings such as:

- Article overview, which summarises the article
- Evidence, which outlines the methodology, trends/patterns/relationships and limitations
- Conclusions, which summarises the evidence
- Relationship to research question, which includes your thoughts and highlights the parts of the research question that this evidence addresses
- Limitations, which identifies aspects of the research question that are not addressed or cannot be answered due to the methodology
- Source- primary/secondary/reference/website (consider whether the information you use is from a primary or secondary source).

Primary and secondary sources

Table 1.15.2 summarises the characteristics of primary and secondary sources. Sometimes the same information may be contained within a primary and a secondary source, depending on when and by whom it was written. For example, a scientist's journal article on a clinical trial of treatments for teenage obesity is a **primary source**, while a general magazine article about teenage obesity, written by a journalist and referring to the scientific study, is a **secondary source**.

TABLE 1.15.2 Summary of primary and secondary sources

	Primary sources	Secondary sources
characteristics	first-hand records of events, experiences, experimental data written at the time the event happened original documents	interpretations of primary sources written by people who did not see or experience the event use information from original documents but rework it
examples	results of experiments scientific journal/magazine articles reports of scientific discoveries photographs, specimens, maps and artefacts interviews with experts websites (if they meet the criteria above)	textbooks biographies newspaper articles magazine articles radio and television documentaries websites that interpret the scientific work of others podcasts

A primary source is written by the observer/witness of an event or the scientist who conducted the research. The information has only been processed by the original observer, therefore it is the least biased of all available sources of information. However, even primary sources may be biased, as the observer or researcher had to make choices related to the observation, control of variables, use of instruments and choices for processing data.

Secondary sources of information are not eyewitness accounts but interpretations of events by other people. As second-hand information, the accuracy and reliability may be reduced, and events may be interpreted through the writer's perception and bias, and there may be ommissions or material taken out of context. You should aim to use a wide range of data sources when using secondary data, to cross-check for accuracy, reliability and validity of information. A single source will not be accepted as 'sufficient'.

When searching for information and evidence, follow these guidelines.

1 Determine if it is a primary or secondary resource.

2 Confirm that it is valid.

- **a** Check that it contains information that is specifically related to the claim.
- **b** Check the evidence and information is pertinent to the variables in the research question.

3 Assess its reliability.

- **a** Is it current/recent information?
- **b** Is it up-to-date in its understanding of relationships?
- **c** Is the evidence equivalent to other sources?
- **d** Check credibility—consider who the author is, their qualifications and expertise.
- **e** Evaluate the methodology, including what variables were controlled or measured.

Articles in scientific journals

Peer-reviewed scientific journals are excellent sources of information. They are usually focused on one area of science with a collection of scientific reports written by scientists who conducted research. The reports and articles found in scientific journals are published primary sources, meaning they are the results of the experiments (Figure 1.15.2 on page e124).

PHYSICAL REVIEW X **14,** 031003 (2024)

Mitigating Temporal Fragility in the XY Surface Code

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An important outstanding challenge that must be overcome in order to fully utilize the XY surface code for correcting biased Pauli noise is the phenomenon of fragile temporal boundaries that arises during the standard logical state-preparation and measurement protocols. To address this challenge we propose a new logical state-preparation protocol based on locally entangling qubits into small Greenberger-Horne-Zeilinger-like states prior to making the stabilizer measurements that place them in the XY-code state. We prove that in this new procedure $O(\sqrt{n})$ high-rate errors along a single lattice boundary can cause a logical failure, leading to an almost quadratic reduction in the number of fault configurations compared to the standard state-preparation approach. Moreover, the code becomes equivalent to a repetition code for high-rate errors, guaranteeing a 50% code-capacity threshold during state preparation for infinitely biased noise. With a simple matching decoder we confirm that our preparation protocol outperforms the standard protocol in terms of both threshold and logical error rate in the fault-tolerant regime where measurements are unreliable and at experimentally realistic biases. We also discuss how our state-preparation protocol can be inverted for similar fragile-boundary-mitigated logical-state measurement.

DOI: 10.1103/PhysRevX.14.031003 Subject Areas: Quantum Information

I. INTRODUCTION

Fault-tolerant, scalable quantum computation with noisy physical hardware relies on encoding quantum information in a large number of physical qubits making up an error correcting code. Two important performance metrics for an error correcting code are its threshold, which is the physical error rate below which error correction becomes successful, and the amount of error suppression possible for a given number of qubits. These depend on its *distance* which sets the minimum weight of an uncorrectable error, the number of fault configurations leading to uncorrectable errors, and their likelihood which heavily depends on the details of underlying noise model [1,2].

Biased-Pauli noise is a common noise model describing many practical qubit architectures in which errors that cause bit flips are far less likely than those that only lead to phase flips [3–10]. When only phase-flip noise is present, we say that the noise is infinitely biased. The discovery of native bias-preserving controlled-NOT gates [9–13] has driven research toward tailoring codes to be highly effective at correcting biased-Pauli noise [14–29]. Two leading candidates for such codes are the XY surface code [19] and XZZX surface code [23]. These are obtained from the standard CSS surface code which consists of X- and Z-type stabilizers by local Clifford deformation of its stabilizers [30]. Their favorable properties arise from the underlying symmetry of their stabilizers due to which these codes reduce to repetition codes when noise is infinitely biased (see Ref. [31] for further discussion on the role of symmetries in error correction). Thus, these codes have a 50% threshold at infinite bias. Moreover, compared to the planar XZZX surface code, the XY code can also tolerate quadratically higher weight phase errors, making it more desirable for correcting strongly biased noise.

It is natural to ask if the favorable properties of the XY code persist during logical state preparation, which is the very first step in any quantum algorithm. In the standard approach, a logical X state $|+_L\rangle$ is prepared by initializing each physical qubit in the $|+\rangle$ state, followed by a measurement of all the code stabilizers. However, in this process half of the stabilizers cannot be used for detecting phase errors, destroying the symmetry of the XY code, a phenomenon that has been referred to as *temporal fragile boundaries* [32,33]. As a consequence, the code does not reduce to a repetition code under pure phase noise and, as we will show, the threshold at infinite bias degrades to ~11%. Moreover, during state preparation the code distance to phase errors scales as $\sqrt{n}$, where n is the number of physical qubits of the code. In contrast, if all the stabilizers

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FIGURE 1.15.2 An extract of an article in a scientific journal of a research report written by scientists. It is strictly structured with a pertinent title, names of authors, an abstract, the report using the convention of: introduction, method, results, analysis, conclusion and ends with a reference list.

Access to scientific journals can be difficult as many journals require you to purchase a subscription or membership, though some are free. Figure 1.15.3 provides ideas for accessing scientific journals.

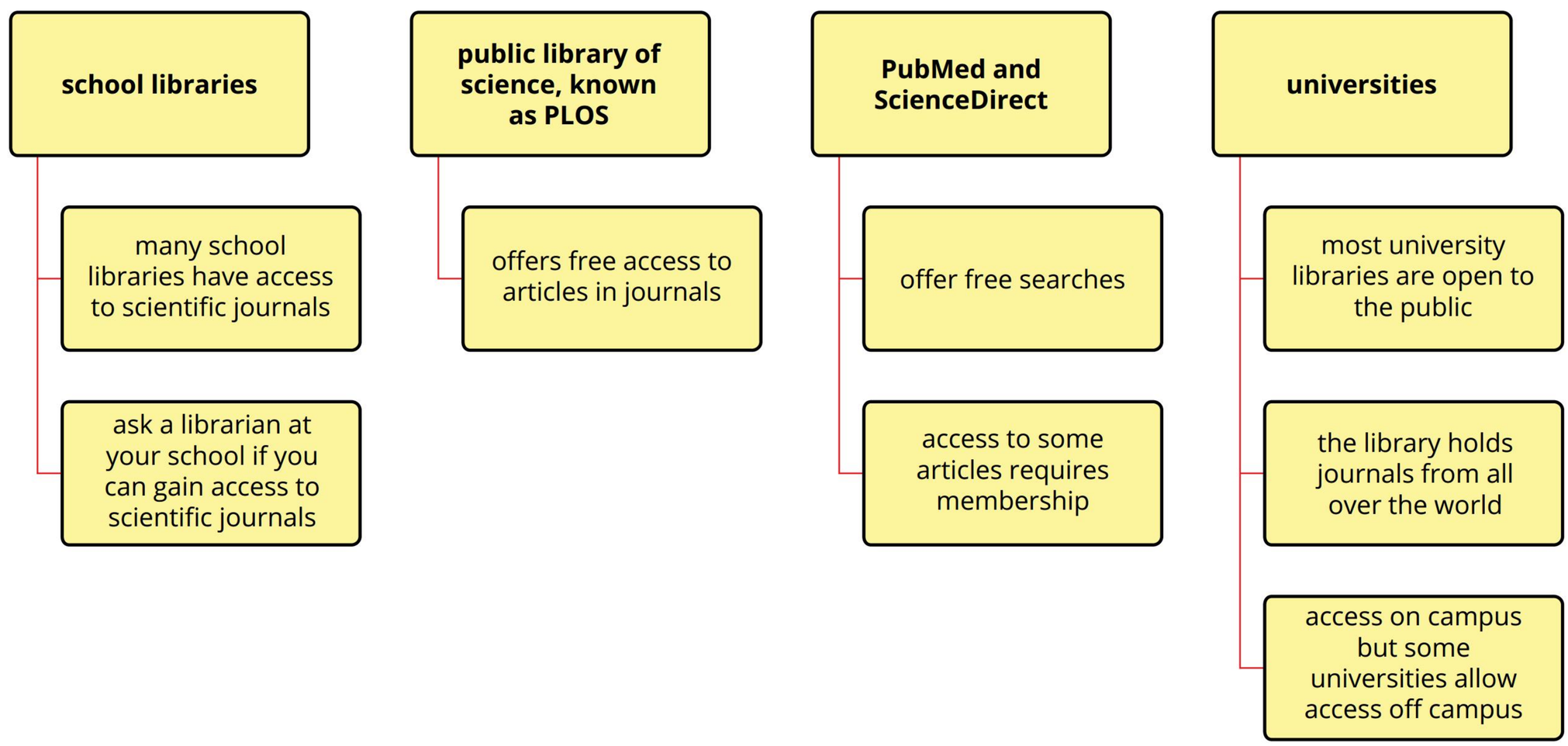


FIGURE 1.15.3 Suggestions and information on accessing scientific journal articles

Scientific articles are excellent sources of information, but also have their drawbacks as sources for the research investigation. Table 1.15.3 outlines some advantages and disadvantages of sourcing and using articles in scientific journals for the research investigation.

TABLE 1.15.3 Advantages and disadvantages of scientific articles

Advantages	Disadvantages
• written by experts • authoritative information (peer-reviewed) • most current information • logical, organised layout • content is relevant to the topic • contains an abstract that summarises all information in the article and saves you reading time. (If you don't find the information in the abstract, the article is not relevant.) • primary source • provides introductory comments that review the literature of the field and position of the research focus of the article in it.	• information is complex and challenging to understand • complex language and advanced processing and analysis of data • requires a high level of scientific literacy, language and numeracy to understand • may be time consuming to read and analyse • well established concepts do not have recent published articles • may be difficult to locate and gain free access to

Books and physical publications

Secondary sources such as good science magazines and books are valuable sources of secondary information.

The first source you should use is your textbook. The language and concepts are presented specifically for high school students and have been carefully reviewed for accuracy. In addition, the textbook addresses the syllabus objectives. Non-fiction books and magazines will probably be commonly used resources for the research investigation. Common commercial science magazines you might find in your school library include *Double Helix*, *Cosmos*, *Scientific American* and *New Scientist* (Figure 1.15.4). Table 1.15.4 on page e126 outlines some advantages and disadvantages of non-fiction books as sources for your research.

FIGURE 1.15.4 A science magazine you might find in your school library

TABLE 1.15.4 Advantages and disadvantages of book resources

Advantages	Disadvantages
• may be written by experts • potentially authoritative information • logical, organised layout • content is relevant to the topic • contain table of contents and index to help find relevant information • easily located in libraries • written in language that is understandable	• may not have been published recently • usable by only one person at a time • may have more bias than primary sources

Searching online

Online sources include online scientific organisations such as CSIRO, NCBI, AIMS, Bioscience (Oxford Academic) and other university publications and press. Many government and privately funded science organisations publish material, along with not-for-profit scientific organisations. Websites may direct you to magazines and scientific journals, such as those described above, the news, podcasts, blogs and videos (institutional, company and personal).

Information located on the internet requires very careful scrutiny. The openness and ease of publishing on the internet means information may not be valid and reliable. Use the earlier guidelines to help you evaluate sources. Table 1.15.5 outlines advantages and disadvantages of locating and using information online.

When searching for relevant information, you need appropriate search terms to enter into a search engine. These tips can help your search:

- Break your search statement into concepts and key words.
- Find synonyms, other related terms and concepts that apply to the topic.
- Create concepts of 1–3 words to enter into the search engine.
- Try different combinations of terms.
- Do not settle for the first sites on the list or your first attempt; look beyond the first page of results.
- Look through the results for sites from science organisations and research institutions (e.g. CSIRO, WEHI, NIH; .gov, .org), universities (.edu) and science journals and magazines.

TABLE 1.15.5 Advantages and disadvantages of internet resources

Advantages	Disadvantages
• quick and easy to access to a range of sources • allows access to hard-to-find information • access to the whole world, millions of websites • information is potentially more up to-date • may be interactive and use animations to enhance understanding • choice of text-based material or images and videos to suit different learning styles	• may not be reliable, valid or credible • can easily side track with non-relevant information • a lot of 'junk' sites and potentially more biased material that may be out of context or unedited • need to discern search engine results to find most useful sites • cannot always tell how up-to-date information is or where it comes from • can be hard to tell who has responsibility for authorship • information may not be well ordered • often is not the original source

Overview of resources

Your textbook should be your first source of reliable information. Other information should be consistent with this. Articles published in journals and magazines often present findings of new research, which may or may not be confirmed later, so be careful not to treat such sources of information as established fact. Scientific journals are **peer-reviewed** (critically reviewed by other specialist scientists), which gives them more credibility than other sources.

However, it is important that the sources utilised in the investigations are credible and easily accessible.

FORMING A QUESTION

The claim is used to develop the research question investigated in the assessment. The variables inferred in the claim may not be measurable or directly observable, and therefore they may not be scientific.

To help to develop the research question, break the claim into possible scientific elements, each of which could be used to form a question (Table 1.15.6 on page e128). Separating the claim into elements, such as related terms and concepts, enables you to formulate variables, measurable items and questions. Thus you can identify scientific elements of the claim that are contained in the syllabus.

Based on these elements formulate a number of questions related to the claim and record all in the journal. The research question must specify a dependent variable and enable a response that will evaluate the validity or the reliability of the claim. You will need to understand the dependent and independent variables, and the relationship between the variables. The research question must identify the dependent variable and may also specify the independent variable.

Some guidelines to help form a research question include:

- identifying a dependent variable that can be linked to the claim or rephrasing the claim into something measurable.
- developing an element of the claim into the independent variable or identifying it in the stimulus material.
- phrasing a question to ask if the independent variable will influence, cause or correlate with the dependent variable.
- writing a few different questions.

Usually, the questions improve as you write more, which allows the formulation of a more developed research question. At this stage these questions can still be quite broad but as they are refined the focus of the research question needs to be very narrow so that the research report can be completed within the assessment conditions.

The process to developing a research question is often cyclical (Figure 1.15.5).

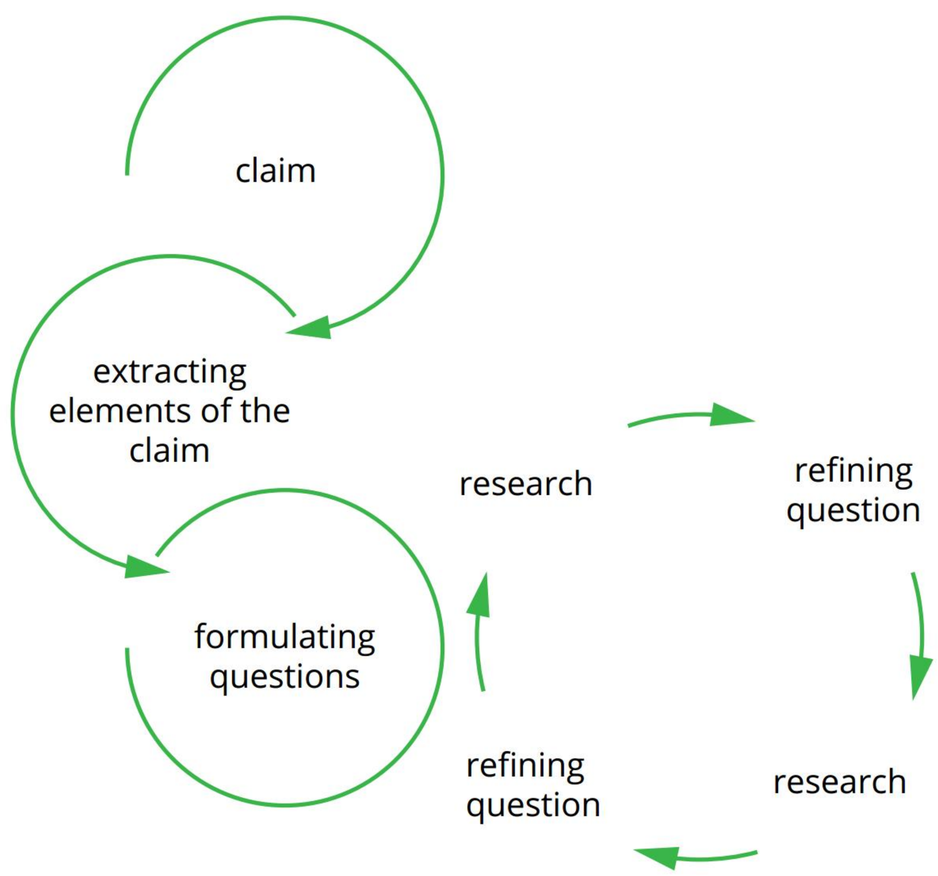


FIGURE 1.15.5 A chart of a common process for developing a research question. This cycle can be repeated as many times as necessary until a scientist is satisfied with the investigation question.

Read through Table 1.15.6 to see examples of questions formed from the elements of the claims that are refined.

TABLE 1.15.6 Examples of questions formulated from a claim

Example Claim 1: Cold fusion could provide a limitless supply of energy to the world.		
Elements	**Elaboration of the claim**	**Formulated questions**
Heat engines require a heat source and a cold sink	The heat source and the cold sink must be different temperatures	Can the temperature of the heat source and cold sink be brought closer together?
Fusion requires high temperature and pressure to start and sustain	Repulsion forces must be overcome	What is the lowest temperature and pressure required to overcome the repulsion forces?

Example Claim 2: Photons are a better source of fuel than atoms		
Elements	**Elaboration of the claim**	**Formulated questions**
Photons are massless	Thrust requires a change in mass with time	Can a massless particle provide thrust?
Storage – batteries	Molecules of fuel store chemical energy.	Can stored photons provide as much power as chemical fuel?
Efficiency	The intensity of light decreases with the inverse squared law	Does the sun emit enough light to allow interstellar travel?

REFINING THE RESEARCH QUESTION

One of the questions in your journal will become your research question. As you conduct research into the independent and dependent variables, new information will refine the question so it is more specific.

Since the forming and finding criterion assesses the development of the research question from the claim, it is important to record your development of conceptual understanding and the knowledge you gain about the relationships between variables.

Table 1.15.7 compares a formulated question with a developed research question. Always get the teacher to assess your research question.

TABLE 1.15.7 Development of the original questions formulated into research questions

Example Claim 1: Cold fusion could provide a limitless supply of energy to the world.		
Formulated question	**Refined research question**	**Variables**
Can the temperature of the heat source and cold sink be brought closer together?	Can the temperature difference between the cold sink and the heat source in a heat engine be decreased without decreasing efficiency?	*Dependent:* efficiency *Independent:* temperature difference
What is the lowest temperature and pressure required to overcome the repulsion forces?	What is the lowest temperature required to overcome the electromagnetic repulsion in the Deuterium–tritium fusion process?	*Dependent:* electromagnetic repulsion *Independent:* temperature

Example Claim 2: Photons are a better source of fuel than atoms		
Formulated question	**Refined research question**	**Variables**
Can a massless particle provide thrust?	Is the quantity of photons required to provide enough thrust to a spacecraft to enable comparable acceleration to traditional chemical propulsion feasible?	*Dependent:* acceleration *Independent: quantity of photons*
Can stored photons provide as much power as chemical fuel?	Is the energy density of electrochemically stored photovoltaics similar to the energy density of chemical fuel?	*Dependent:* energy density *Independent:* type of fuel
Does the sun emit enough light to allow interstellar travel?	Is the intensity of light emitted by the sun sufficient to accelerate a craft to 0.1c before it leaves the solar system	*Dependent:* acceleration *Independent:* intensity of light

Your research investigation report requires a considered rationale for the research question, displaying its clear development from the claim. Outline this step-by-step development, justifying the steps using scientific concepts, knowledge and understanding.

Your research question must explicitly identify the dependent and independent variables. The research question must be connected to the considered rationale and the topic of study.

PUTTING IT ALL TOGETHER

The structure of the research report is not mandated by the assessment specifications but needs to be presented using appropriate report conventions, such as appropriate headings and language, and acknowledge the source of the information using referencing conventions (see module 1.8).

Possible report structures include headings such as:

- Claim, Rationale, Research question, Introduction or Background, Analysis and Interpretation, Conclusion and Evaluation,
- Or organised under the headings of the instrument-specific marking guide (ISMG) criteria as stated in the QCAA syllabus; Forming and Finding, Analysing, Interpreting and Evaluating
- Or you may elect to organise your report in a different but logical order.

The sample research investigation report that follows, covers the ISMG criteria and may be used as a reference tool. Use this as a model for reference.

Forming and finding

Claim: No Air Conditioner Needed: These Buildings Cool Themselves

Rationale

The article linked to the above claim focuses on uses of bioclimatic building design in Pomona, California which uses ventilation and airflow rather than air-conditioning to cool the building and as a result significantly reduces the need for mechanical cooling and reduces its energy consumption (Wetsman, 2018). In 2022, Queensland was responsible for 25% of energy consumption of the whole country (Australian Government, 2022), so significantly reducing its energy consumption would have a large effect on the rest of Australia. As stated in the article "depending on where you are, you'll implement different techniques" (Wetsman, 2018), therefore this report will explore different building design techniques that could potentially be implemented in Queensland (QLD).

However, the claim is a broad statement and some aspects of it must be specified more clearly to accurately investigate it, for example, 'cool themselves'. The average temperature in Pomona, California in the summer is 87°F (Weather Spark, 2024). (roughly 30°C), the article agrees and additionally claims that the building is cooled to a 'very comfortable' 73°F, or approximately 22°C. In QLD the average temperature moderated by air-conditioning is around 25°C (Gall, 2023), therefore this investigation will focus on whether bioclimatic design techniques would reliably cool buildings to or close to 25°C. There are many techniques designed to cool buildings, types of insulation, green roofs, double glazed windows for example. 'Old Queenslander' style homes were "designed for a sub-tropical climate,...[and thus were]...elevated above-ground to allow air to flow underneath for increased ventilation" (Homes to Love, 2022). Though modern architecture has shifted its priorities away from ventilation.

Furthermore, the claim just references 'buildings' though there are many different types of buildings with different features and therefore different ideal ways of using bioclimatic design to cool those buildings. For example, residential homes often have slanted roofs and are relatively shorter compared to office buildings and community buildings such as schools. This investigation will focus on bioclimatic design features most suited towards office buildings, both built in the future and that are already finished. For this reason, ventilation in a similar style to that of an 'Old Queenslander' house would not be feasible for tall and already grounded office buildings. Office buildings typically have flat roofs and windows on all sides and across the length of the wall, meaning they could be suitable for additions of solar control window film and rooftop gardens. Solar control window film is applied to the window glass and is designed to absorb most of the heat that the windows would otherwise let through, which could be crucial for a building with as many windows as an office tends to have (Li, Tan, Chow, & Qiu, 2015). Research into rooftop gardens also shows they can absorb heat and reduce heat transfer through the roof, which again could have a large effect on the overall temperature of the building (Wong, et al., 2002). This report will investigate the potential benefits and effects of solar control window films and rooftop gardens on office buildings.

Research question

Within Queensland, is it viable to reduce the need for air-conditioning, and therefore energy consumption, in existing office buildings with solar control window films and rooftop gardens such that the building's inside temperature remains at or around 25°C (Gall, 2023)?

1.16 Analysing

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- identify the variables in the research question
- determine the evidence required to evaluate the validity of the research question
- identify relevant patterns and trends in the data
- explain the patterns between the two variables
- identify the limitations or gaps exist in evidence.

The Analysing criterion is assessed in relation to just the identification of enough data that enables the research question to be answered and identify the limitations of the sources of the data.

Analysing evidence describes relationships between dependent and independent variables. The data should be presented from more than one source and the overall trend from several authors needs to be identified.

ANALYSING EVIDENCE

A trend or pattern is a general change in one characteristic with respect to another. In science, these are generally represented in the form of a graph with the dependent variable on the *y*-axis and the independent variable on the *x*-axis. Refer also to the graphing information in Module 1.6 of Part A.

The first thing to notice about a trend is the shape of the graph. If there is a relationship between two variables the trends can typically be categorised into one of five categories; linear, power, inverse, exponential and logarithmic.

Figure 1.16.1 shows a comparison of two linear trends. The graph shows the change in the mass of product as a function of time. While a trendline for each is shown no error bars are included for this discussion. When analysing relationships, it can be necessary to compare the effects of changing conditions on the dependent variable. As well as determining the gradients of the curves, key features such the *x*- and *y*-intercepts are important. While both linear graphs show that as time increases the mass of product increases, the rate of increase or gradient is greater for the dashed line. The dashed line passes through the origin, whilst the solid line extrapolates at a negative intercept.

Note, the analysis criterion identifies the relationship but does not assess the reasons for the relationship. That will be assessed in the Interpreting criterion.

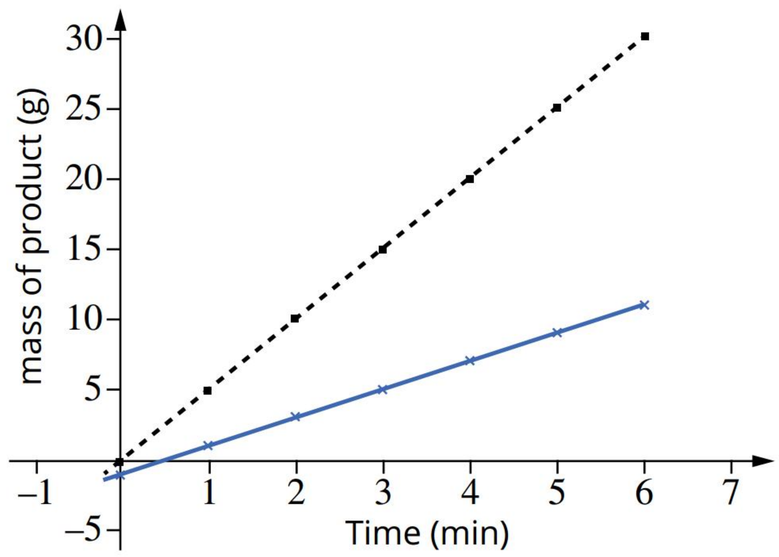


FIGURE 1.16.1 Comparison of the formation of product of a reaction under different conditions

Look at Figure 1.8.3 on page e77. It shows an example of research evidence and how it can be reinterpreted. Figure 1.8.3a shows the original evidence that the student found through research (data is of the light curve of distant star as an exoplanet passes in front of it). Figure 1.8.3b is the student record of their interpretation of the evidence found in the resource.

LIMITATIONS OF THE DATA

All studies are affected by limitations. So, when analysing the data it is important to identify the limitations. Limitations can often be grouped into three categories:

- Elements of the methodology
- Study design that impacts the interpretation of the research results
- Differences between the studies or sources used to investigate the relationship.

Examples of common methodological issues

Table 1.16.1 outlines some examples of methodological issues that can arise in your research.

TABLE 1.16.1 Common methodological issues

Methodological issue	Explanation
selection of samples	This can result in a selection bias if the sampling method results in the selection of samples that do not reflect the general population or population concerned.
insufficient sample size for statistical measurements	It is critical to have a sufficient sample size to draw valid conclusions. More precise results can be obtained if a larger number of samples are collected, which also enable the results to be generalised to a larger population. In contrast, if the sample size is too small it can be difficult to identify significant relationships in the data.
lack of previous research studies on the topic	If the research cited is one of a limited number into the issue the lack of available or reliable data can be difficult to make firm conclusions or make connections between studies or the findings and the real world.
methods/instruments/ techniques used to collect the data	While it is unlikely that the students will have experience in using many of the instruments used to collect the data, the limitations in the methodology should be outlined in the discussion section of the research paper. This could include but is not limited to the instruments level of detection.
differences between the studies or sources used to investigate the relationship	While they may have the same dependent and independent variables, they are unlikely to have used the same methods, materials, or context. Additionally, even if studies elucidate the same relationship between variables, they may show differences in the degree or extent of the relationship. For example, foam batt insulation installed in houses in Canada experience a different range of temperatures than houses in Australia. Findings from studies from different countries would have to be compared with this difference in context in mind.

When reading the research papers, refer to the collection of sufficient and relevant raw data in Part B. This will help evaluate the analysis of the data and identify limitations of the methodology.

As with identification of the trends and patterns, the analysis criterion only assesses the identification of the limitations of the research. The role these limitations played on the data collect and potential impact of the study, including the inability to generalise the research findings will form part of the Evaluating criterion section.

Furthermore, the report should discuss possible ways to overcome the limitations in future studies, such as alternative methodologies and ways to avoid issues.

Ways to discuss the limitations

When identifying the limitations of the study there are ways to introduce the discussion on the limitations.

- Possible limitations of the study include …
- The first is the…The second limitation concerns the…
- The empirical results reported by … should be considered in the light of some limitations.
- This research is subject to several limitations.
- The primary limitation to the application of these results is…
- The design of the current study is subject to limitations.
- The major limitations in this study that could be addressed in future research are firstly, the study focused on …. Second …
- Having data sources that have used different testing methods or materials can create limitations in the ability to answer the research question. For example, vehicle crash test results from NCAP (Europe) and ANCAP (Australia) use slightly different testing methods which may introduce limitations when it comes to comparison. Note that you will be using data from a number of sources to determine the overall trend, and it is unlikely that these researchers used exactly the same methods or materials.

Sufficient and relevant

Similarly when deciding whether the sources are relevant or sufficient, refer to the start of this module. The analysis criterion uses the terms sufficient and relevant. However, in this case the terms refer to the evidence. Was the data that was analysed 'enough and connected with the investigation' to enable the research question to be fully answered.

PUTTING IT ALL TOGETHER

When writing the research report, it is important to evaluate the report against each criterion in the ISMG to assess the quality of the response. The analysis criterion is focused on the evidence that is collected, and identifying and describing patterns or trends that are evident and connected to the research question. Therefore, it is critical that a student identifies aspects of the research question that need to be answered. This will enable the searching for and selection of information related to these aspects.

Once the evidence has been found, the trends need to be identified and used to answer the research question. Remember, that the analysis criterion is only assessed against identification of the patterns and identifying the limitations of the research. So, to get the highest mark, the report needs to collect and analyse enough information to answer the research question.

The sample research investigation report that follows, covers the ISMG criteria and may be used as a reference tool. Use this as a model for reference.

The sample research investigation report shows the analysis of evidence for the research question developed from the claim and covers the ISMG criteria. It may be used as a reference tool. Use this as a model for reference.

Analysing

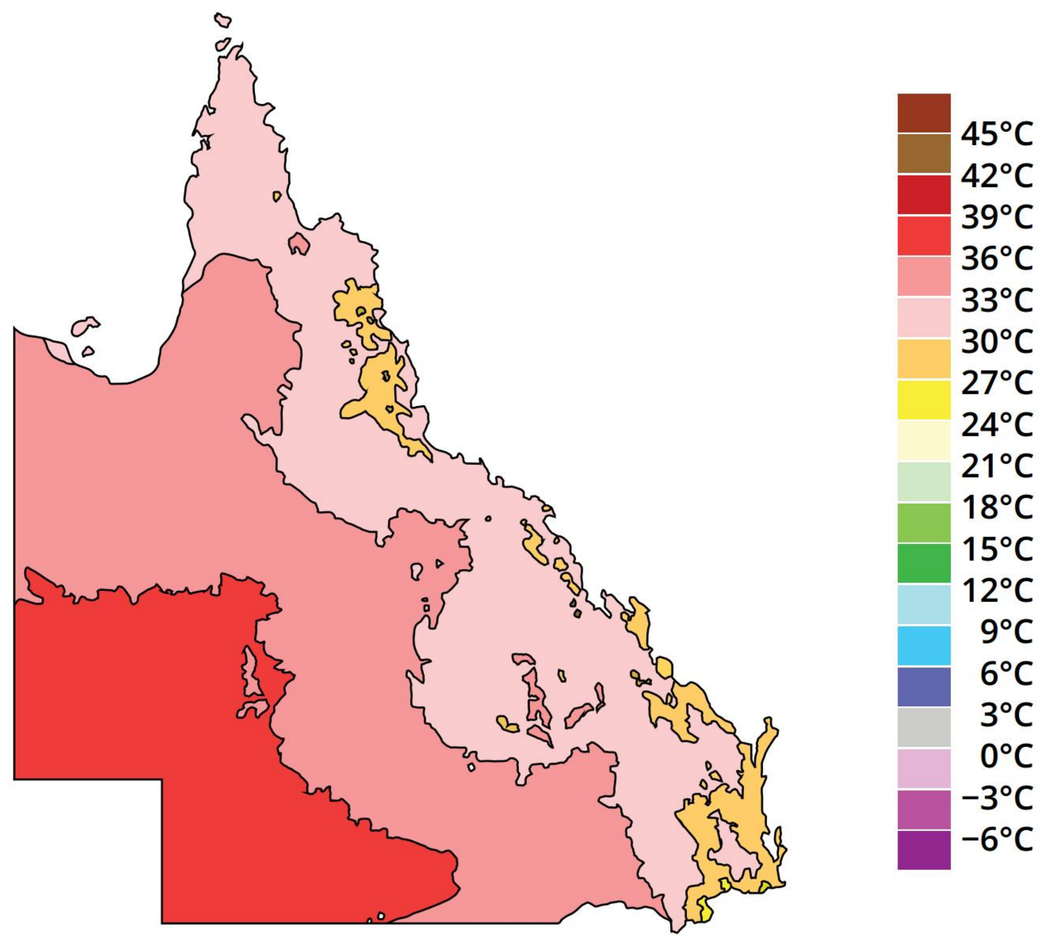


FIGURE 1 Mean daily maximum temperature across Queensland in 2023 (Bureau of Meteorology, 2023)

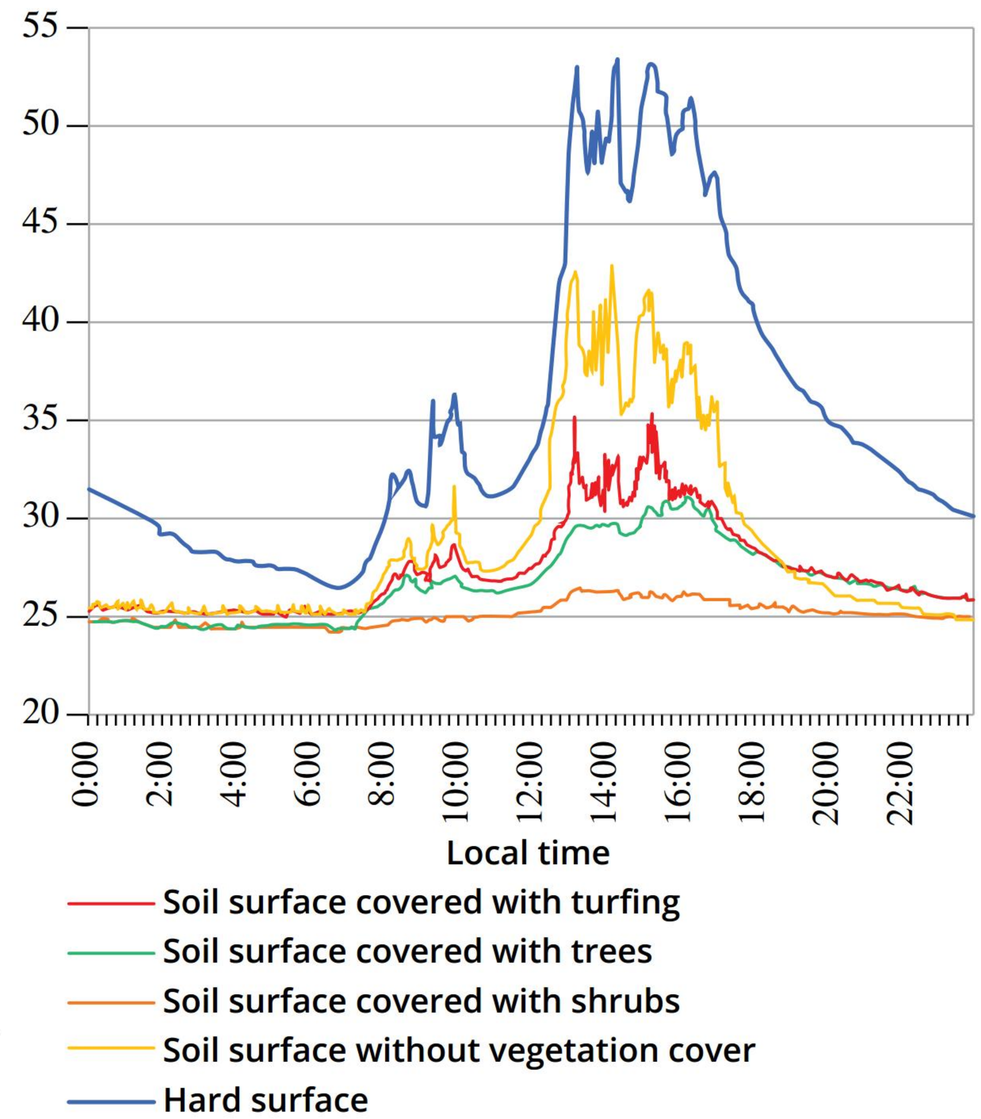


FIGURE 2 Comparison of measured surface area temperatures of multi-story office buildings with different kinds of plants (Wong, et al., (2002))

It can be seen in Figure 1 that the mean daily maximum temperature across QLD is between 27°C and 36°C. Office buildings are mostly located in South-East QLD (SEQ) where the mean daily maximum is between 27°C and 30°C. The mean daily maximum range for SEQ is within the range of exterior temperatures used for Figure 2's experimental data, which shows a green roof made of shrubs can cool a multi-story office building to a relatively stable 25°C throughout the day from an exterior temperature of between 25°C and 30°C (stated in rest of report from (Wong, et al., 2002)). Together they suggest that rooftop gardens would be a successful in cooling office building interiors to 25°C, provided the gardens are shrubbery gardens, in the SEQ climate (which has an average daily maximum of 27–30°C) as they were able to do so in a similar climate successfully. In addition, as green roofs are able to cool down building interiors, it can be assumed that it also limits the need for air-conditioning and reduces the building's overall energy consumption.

However, both figures have limitations that effect the accurateness of the data. Figure 1 does not show how the daily maximum temperature is changing over time and may not be representative of the overall temperatures that occur in the QLD climate, therefore reducing the accuracy of the relationship identified (green roofs may not be effective enough to reduce temperatures). Furthermore, the experiment represented in Figure 2 was undertaken in Singapore only has a similar climate to QLD and not the same one (the average temperature in Singapore is 6.1°C warmer than QLD (Climatemps, 2015)) as a result the green roofs again may not be effective enough to reduce interior temperatures to 25°C.

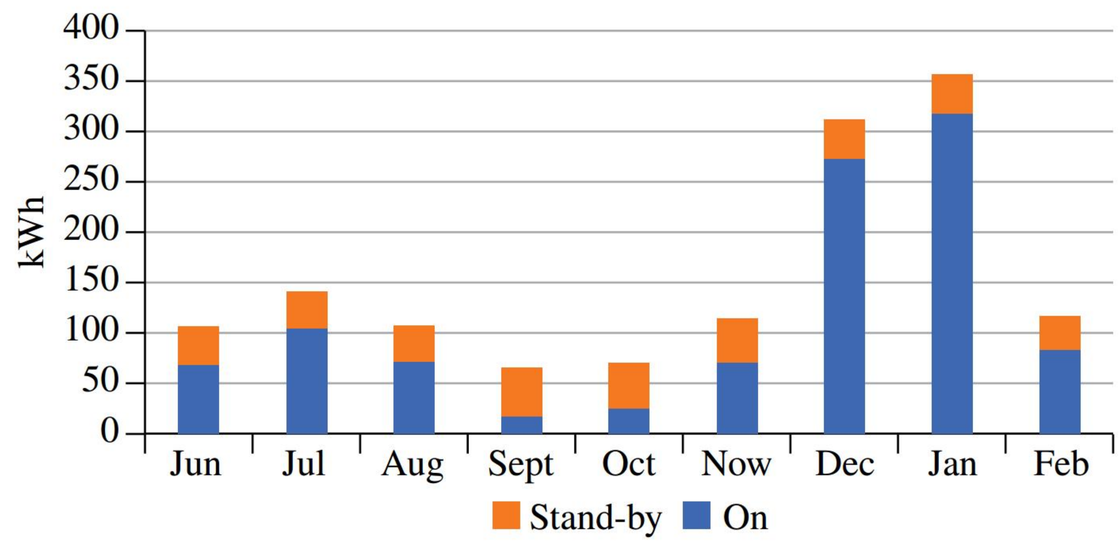


FIGURE 3 Air conditioning run and standby monthly energy consumptions, Brisbane (Law, Osman, Ambrose, James, & White, (2014))

Case no.	Descriptions	Solar film on glazing facing all directions		Solar film only on glazing facing west	
		kWh (%)	kWh/m²	kWh (%)	kWh/m²
1	12 mm clear glazing with SF-1 attached	15,435 (9.5)	44.6	6624 (4.1)	76.7
2	12 mm clear glazing with SF-2 attached	21,253 (13.1)	61.5	7753 (4.8)	89.7
3	12 mm grey tinted glazing with SF-1 attached	3906 (2.7)	11.3	1353 (0.9)	15.7
4	12 mm laminated glazing with SF-3 attached	9272 (5.9)	26.8	2601 (1.7)	34.9
5	6 mm double clear glazing with SF-1 attached	7592 (4.7)	22.0	2911 (1.8)	33.7

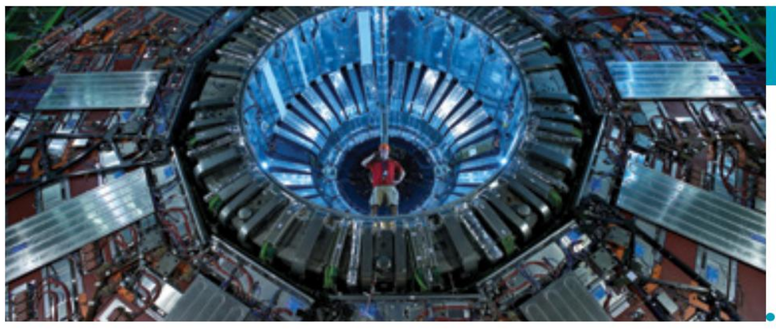
FIGURE 4 Electricity saving for an office building with solar window film applied in 5 cases (Li, Tan, Chow, & Qui, (2015))

Figure 3 shows that during the summer months (December, January and February), Brisbane consumes significantly more energy via air-conditioning, 669 kWh running and 184 kWh on standby, than during the winter months (June, July, August), 243 kWh running and 114 kWh on standby, and spring months (September, October, November), 112 kWh running and 137 kWh on standby.

Figure 4 conveys the experimental energy saving capabilities of solar control window film through reducing air-conditioning requirements. The maximum potential energy reduction shown in the experiment is 13.1% and, after applying that reduction to the data from Figure 3, solar control window film has the potential to reduce Brisbane's energy consumption to 581 kWh (–88 kWh) in the summer months. Building interiors would be cooled (though the actual quantitative reduction temperature is uncertain) and as a result reducing the need for air-conditioning. Again, however, both data sets are limited in their accuracy.

The data in Figure 3 relates to air-conditioning of households. This report investigates effects of bioclimatic design on office buildings, which would have a higher energy consumption in comparison, but also most likely contains more windows, so the window film could easily be either more or less effective than predicted. Additionally, the measure of energy consumption reduction in Figure 4 may be specific to one office building and/or one type of air-conditioner and therefore it may not be correct to apply its data to all office buildings. For example, some air-conditioners are more efficient than others so the energy reduction would be greater on most other air-conditioners, or, the building may have had a lower than average number of windows making the film less effective so the energy reduction would also be greater on other buildings that had more windows.

1.17 Interpreting



BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- evaluate the research process
- understand the steps and requirements for a justified argument
- identify the steps necessary to develop a justifiable conclusion.

The interpreting criterion is assessed in relation to creating scientific arguments and conclusion and use of scientific language to address the research question.

To achieve the highest mark (5) in the Interpreting criterion you need to create justified scientific arguments and a justified conclusion to answer the research question and present the results in the form of a scientific report using fluent language and representations.

JUSTIFYING AN ARGUMENT

When constructing a scientific argument, the claim, the evidence and the scientific reasoning need to be considered.

- The claim is a statement about a particular phenomenon or observation.
- The evidence is what is known.
- The scientific reasoning is why does the evidence support or refute the claim.

The QCAA glossary defines 'justify' as 'to give reasons or evidence to support an answer, response or conclusion; show or prove how an argument, statement or conclusion is right or reasonable'.

A scientific argument is a statement, supported by multiple pieces of evidence, that is measured or observed. The argument links the evidence and reasoning together with scientific facts and knowledge. It is important to recognise that the argument could either corroborate the claim or provide evidence that refutes the claim.

Therefore, the investigation needs to use the information and evidence collected from the research to answer the research question rather than simply opinions or beliefs that cannot be empirically verified.

The Introduction outlined terms and concepts related to the topic, which were used to develop the research question. This helped identify variables linked to the research question to be analysed. Then the Analysis section of the report identified patterns and trends in the data related to the research topic.

The Interpreting section of the report needs to explain the trends between the variables to explain the research question.

Common things to avoid

When writing the justification, it is important to be concise and to the point. Select data and explain how the evidence is linked to the research question. Ignore evidence that has no relevance to the research question.

Be selective about the information discussed; the specifications of the assessment task state that the length of the report is limited to 2000 words. The justification needs to emphasise the significance of the research to the research question or topic. How do the trends identified in the analysis section support the conclusion that was drawn? If the data does not directly address the question it should be removed from the report. It is not necessary to use the whole of the data from the research; only use parts of the data that address the research question.

DRAWING A CONCLUSION

When writing the conclusion *make* sure that it explicitly answers the research question. The easiest way to do this is to state the research question and summarise how the evidence supports the research question in about 150 words. In the summary, refer to the key evidence and authors or figures. In addition, concisely outline key limitations and how they contradict the conclusion with respect to the research question. The conclusion usually contains the scientific argument for the dependent and independent variables' relationship that has been identified.

The conclusion is sometimes positioned after the analysis and sometimes at the end of the report. Its placement in your report will need to make sense to you and maintain the flow of ideas:

Option 1: Forming and finding → analysis → conclusion → evaluation

Option 2: Forming and finding → analysis → evaluation → conclusion

The student sample provided on page e115 of this chapter uses the first of these options, grouped together under the heading 'Conclusion and Evaluation'.

PUTTING IT ALL TOGETHER

There is no single way of creating a justified argument to answer the research question or write the conclusion. The interpretation of the research collected simply needs to create justified *arguments* that use the evidence to explain and answer the research question to form a justified conclusion.

The following conclusion and evaluation is for the sample research investigation report from section 1.16 Analysing. It may be used as a reference tool. Use this as a model for reference.

Interpreting

Conclusion and evaluation

Overall, the evidence found in this investigation supports the research question and agrees it would be viable to reduce the need for air-conditioning in QLD's existing office buildings, by at least 13.1% and in addition reduce energy consumption, by using solar control window films and rooftop gardens to cool the interior of the building from an exterior temperature of between 25°C and 30°C to around 25°C. From Figures 1 and 2, it can be inferred that rooftop gardens will be able to cool office building interiors to a comfortable temperature despite the hot summer QLD temperatures (27°C and 30°C). Furthermore, Figures 3 and 4 demonstrate how total energy consumption in summer could be significantly reduced from 669 kWh to 581 kWh by reducing the need for air-conditioning.

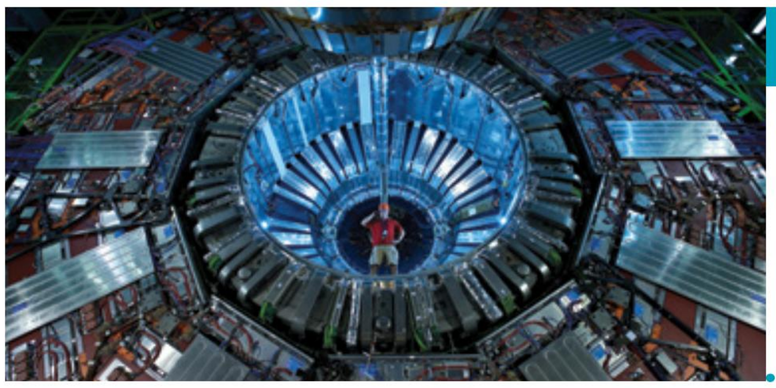
Quality of evidence

As shown by the Quality of Evidence table (Appendix 1), the evidence used to form this conclusion is highly relevant to the topic, peer-reviewed and/or from a reputable publisher and consistent with other credible sources. However, three of the four pieces of evidence were produced more than 5 years ago, up to 22 years ago, meaning that they possibly do not reflect contemporary technology as accurately as they could, though each of them was published as part of an experiment or report where there was otherwise limited additional, more current research. Figure 2, the oldest produced 22 years ago, was part of an investigation into the effects of rooftop gardens on interior building temperature, therefore in the time since its production there may have been advances in technology that improve the effectiveness of the gardens or evidence that a different type of plant may be more effective than shrubbery. Figure 3 shows energy consumption from air-conditionings from 10 years ago, air-conditionings may have become more energy efficient since then. Finally, Figure 4, similar to Figure 2, was part of an investigation into the effects of solar control window film, the technology for which may also have improved in the 9 years since its publication to become more effective in energy reduction and interior cooling.

Extrapolation

The findings of this investigation do not refute the original claim, No Air Conditioner Needed: These Buildings Cool Themselves, although not all aspects of the claim were not considered. These aspects include: cooling different types of buildings; applicability to the rest of Australia and other different climates; and other bioclimatic techniques that could be used for the same purpose.

1.18 Evaluating



BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- evaluate the research process
- identify the steps necessary to develop a justifiable conclusion
- evaluate the quality of the evidence
- extrapolate the conclusion to the original claim.

The evaluating criterion is assessed in relation to evaluating the quality of the evidence, connecting the information to the original claim and suggesting improvements and extensions that relate to the claim.

To achieve the highest mark (5) in the evaluating criterion you need to evaluate the quality of information used to support the scientific arguments. This requires an explanation of the limitations of the data including an assessment of the statistical quality of the data, such as R value or error bars. In addition, while the focus of the report is to justify a very narrow research question, this section needs to generalise the findings to the much wider claim, i.e. if the findings were more widely applicable how this would impact the claim. Finally, what improvements and extensions would strengthen the findings and further justify the answer to the research question.

EVALUATE THE QUALITY OF EVIDENCE

The analysis section of the report identified limitations in the data. This section of the report needs to explain the how the limitations in the data identified and the sources used to support the argument affected the ability to evaluate and answer the research question.

Questions that could be useful to answer when evaluating the reliability of the data include:

- Were the statistical measures of the data good and appropriate?
  - This could be through an R value close to 1, or very small error bars in the data trend.
- Was the sample size sufficient to say that the findings were valid?
  - As the sample size increases the standard deviation of the results decreases, meaning that the chance of results being skewed by a single outlier is less.
- Were the findings reproducible?
  - The results of the research investigation were corroborated by other studies and research institutions.
  - The experiments in the study were repeated with different techniques and the findings were consistent or independent of the methodology chosen, without a justifiable reason why they might vary.
- Did the result occur only under very specific conditions and were these conditions applicable to the real world scenario?
- Was the methodology and instrumentation able to be applied appropriately to the situation studied?
- If the study had to investigate concentrations significantly greater than those that exist in the real-world can the findings of the research be applied to the real world?
- Are the theories that the authors used to support their findings still valid?

It is important not to just repeat the statements earlier in the analysis but to describe the effect on the investigation.

In addition to evaluating the data analysed the investigation needs to evaluate whether the sources that were used were reliable.

EVALUATING SOURCES FOR VALIDITY AND RELIABILITY

Determining the validity and reliability of a source can be a challenging task. For some sources, it is easy to find details about the author and quality of the evidence, while others only contain content and do not offer any other details. Another difficulty is when learning about a new topic or concept, we are all novice learners so it can be challenging to tell if a source is valid or not.

Examples of questions to consider when evaluating the sources include:

- Who or what organisation commissioned the report?
- What qualifications do the authors have?
- Is the source peer-reviewed or have a bias that might influence their findings?
- Is the information provided referenced and are the sources of this information reliable?
- When was the research reported? This is important as theories and concepts can be influenced by the year in which they were published.
- Are the findings reported in the publication supported by other sources? This will be found in the introduction, where the author identifies background information and gaps in the current understanding of the topic.

Table 1.18.1 outlines an example of evaluating a resource step-by-step, for the research article (Figure 1.18.1) that is connected to a claim about the effect of silica aerogel particle size on its performance in composite materials for thermal insulation and sound proofing. Connected to a claim comparing herbal shampoo with commercial shampoos.

Effect of silica aerogel on thermal insulation and acoustic absorption of geopolymer foam composites: The role of aerogel particle size

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ABSTRACT

Silica aerogel features super thermal insulating and excellent sound absorption. Although the application of silica aerogel in building materials for energy saving has been investigated recently, the role of aerogel particle size on geopolymer foam render can be crucial but is rarely studied. In this research, four kinds of silica aerogel with different particle sizes (2–40 μm, 100–700 μm, 100–1200 μm, 700–4000 μm) are applied in geopolymer foam aerogel render (GFAR) to improve the thermal insulation and acoustic absorption performance. Results show that larger silica aerogel particles are more beneficial for acoustic absorption and thermal insulation while smaller aerogel particles are less effective for insulation properties. The microstructure of GFAR is investigated in-depth with micro-CT, optical microscopy and ultrasonic pulse velocity test. The mechanism of the improved performance of GFAR with different silica aerogel is explained. The optimal geopolymer foam aerogel render (GFAR) reaches a thermal conductivity of 0.133 W/(m·K), an average value of acoustic absorption coefficient of 0.51 with a density of 715.2 kg/m^3. The result of this study is essential to enlighten the use of larger silica aerogel particles in geopolymer foam render, focusing on a low dosage of silica aerogel while utilize its full benefit.

1. Introduction

The energy-saving of the building sector and the comfort of the indoor living environment have received rising attention due to the increasing awareness of sustainability and the quality of life [1]. The building industry is responsible for almost 40% of the total energy and CO_2 emission in developed countries [2]. For now, many countries have already initiated policies to decrease heat loss through building shells [3]. Moreover, the functionalization of insulation materials is also very important, for instance, improving the acoustic absorption performance to increase the quietness of the indoor environment [4,5] and reduce the noise pollution generated from daily life [6]. Therefore, developing newly high-performance insulating lightweight materials is of significant urgency.

Silica aerogel is a super-insulating inorganic material [7], consisting of a 3D network of crosslinking silica nanoparticles and 95%–99% of air [8]. Thanks to the high porosity and low solid thermal conductivity (λ), the effective thermal conductivity of silica aerogel is pretty low, normally achieving 0.012–0.018 W/(m·K) [9]. However, the silica aerogel is very brittle and easy to break, the commercial silica aerogels are always produced in a powder or particle form [10]. It is often incorporated in other matrices, like fibreglass mats or other lightweight materials to facilitate its benefits [11]. Several investigations related to the incorporation of silica aerogel in building materials have already been carried out as presented in Table 1. Ng et al. [12] prepared high-performance aerogel concrete, with bulk density and thermal conductivity of 1300 kg/m^3 and 0.4–0.5 W/(m·K), respectively. The concrete has a low water to binder ratio of 0.20–0.25 and a silica aerogel replacement ratio of 50%–70% with sand. Tao et al. [13] developed normal cement mortar with an aerogel replacement ratio of 60%, featuring a compressive strength of 8.3 MPa and thermal conductivity of 0.26 W/(m·K). Júlio et al. [14] prepared lightweight aerogel aggregate concrete with a 100% replacement ratio of silica aerogel with sand, resulting in concrete with very low thermal conductivity of 0.085 W/(m·K) but compressive strength of only 0.41 MPa. Seo et al. [15] investigated the silica aerogel used in fly ash/slag geopolymer concrete, with an aerogel concentration of 25%–75%. However, the thermal conductivity is relatively high, reaching 0.8 W/(m·K). Zhu et al. [16] investigated the cement-based mortars and coatings with the addition of silica aerogel. The thermal conductivity is low (0.17 W/(m·K)) with a

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1359-8368/© 2022 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

FIGURE 1.18.1 A peer-reviewed research article entitled 'Effect of silica aerogel on thermal insulation and acoustic absorption of geopolymer foam composites: The role of aerogel particle size'

TABLE 1.18.1 Evaluation of a resource

Source evaluated: Effect of silica aerogel on thermal insulation and acoustic absorption of geopolymer foam composites: The role of aerogel particle size'

Criteria		Decision	Support/justification
Primary or secondary	Is this an eyewitness account or a second-hand source?	primary	• Research article published in www.Sciencedirect.com • Research results published in article
Validity	Does it contain information that is specifically related to the claim?	yes	• Outlines information directly related to the performance aerogel as thermal insulation
	Is the evidence and information pertinent to the variables in the research question?	yes	• Information, experiment and results are specific to the performance and physiochemical properties of aerogel.
Reliability	Is it current/recent information?	yes	• Published Aug 2022 • This is quite recent, but aerogels are modern materials undergoing a considerable amount of research. There may be newer information available.
	Is it up-to-date in its understanding of relationships?	yes	• Information outlined about thermal conductivity and properties of aerogel
	Is the evidence equivalent to other sources?	mostly	• Table 1 within the article contains a list of six similar experiments.
	Check the credibility—consider who the author is, their qualifications and expertise.	good	authors are from the School of Civil Engineering at Wuhan University or the Department of the Built Environment at Eindhoven University journal of Basic and Applied sciences is a reputable peer-reviewed journal
	Try to find the sample size.	known	Six samples, three trials per sample.
	Try to establish what variables were controlled or measured.	known	methodology of the preparation, storage, and testing of the samples is detailed, including controled variables such as air temperature and humidity.

A judgement could be made about the credibility of this source, such as:

The information and evidence was published by experts in a peer-reviewed journal article that is up-to-date and with variables of experimentation known and directly related to the claim and research question. Though as the results are new, it is yet to be seen if they are substantiated, therefore affecting the reliability of the evidence. This resource is both valid and reliable.

EXTRAPOLATION TO THE CLAIM

The first stage of this assessment involved narrowing the claim to a very specific research question. This could have meant selecting a specific material or smaller temperature or concentration range. The Extrapolating criterion requires inferring how the trends and patterns identified and explained in the earlier sections of the research report could be extended to the original claim.

When exploring the claim, the students identified the dependent and independent variables associated with the claim. Thus, questions that can help students extrapolate the findings and conclusion to the claim include:

- what are the dependent, independent and controlled variables associated with the claim?
- what is the impact on the dependent variable when the independent or controlled variables from the research question are extended to include the claim?

IMPROVEMENTS AND EXTENSIONS

Suggest improvements and extension(s) that would complement the research findings and have the potential to provide new evidence that could be used to evaluate the research question (improvements) and claim (extensions) further. These should be linked to the identified limitations (analysis and quality of evidence can just identify the issue). Make sure not to repeat yourself.

The highest performance level requires that suggested improvements need to be considered and relevant. There are two obvious areas that could be the focus of the suggested improvements. Firstly, a good place to start when proposing possible improvements is the limitations in the research and evidence that were identified and explored in the previous sections in the report. Secondly, what information is required to provide more definitive proof of the research question.

As discussed in the limitation, these could come from the methodology or the interpretation of the results. It could be useful to consider the following:

- changes to the method of selecting samples to reduce bias
- increasing the sample size to increase the accuracy of the results or reduce the errors associated with the measurements
- methods/instruments/techniques used to collect the data. If the measurements were below the limit of detection or so low that the associated error was large. Has technology advanced since the previous research that mean that the relationship can be more accurately determined.
- through your investigation what gaps in the evidence did you identify.

These considerations could form the basis for your suggested improvements. While a detailed explanation of these is not required, the report should identify how they would benefit your investigation.

Suggestions of possible extensions to the research investigation could be identified from the information collected as part of the research investigation. Students should ask themselves if there were limits to the scope of evidence available.

- Did the research you found identify areas that could be explored further?
- Could the conclusions from your report be extended to another situation?
- When extrapolating the research question to the claim, were the aspects that could not be proven because the information was not available?

PUTTING IT ALL TOGETHER

There is no singular way of creating a justified argument to answer the research question or write the conclusion. The interpretation of the research collected simply needs to create justified arguments that use the evidence to explain and answer the research question to form a justified conclusion.

The sample research investigation report that follows, covers the ISMG criteria and may be used as a reference tool. Use this as a model for reference for justified arguments that link the research question and evidence, enabling a conclusion supported by reasoning and scientific understanding to be drawn.

The sample research investigation report that follows, covers the ISMG criteria and may be used as a reference tool. Use this as a model for reference.

Conclusion & Evaluation

Improvements and extensions

To fully investigate all aspects of the claim, there are several improvements and extensions that could be made. This report focused on office buildings, however its conclusion could be improved by considering its applicability to other types of buildings, such as residential homes, apartment buildings, community buildings and commercial buildings, and how green roofs and solar control window film could benefit them as well as the effects on a specific building in QLD to gauge specific and quantitative cooling effects from the window film and garden. It could also be improved by investigating the distinct combined effects of both green roofs and the window film to see exactly how much of an effect they would have together instead of just 'an effect'. Additionally, this research could be extended by investigating other bioclimatic techniques for reducing temperature, such as insulation, ventilation and shade etc, which could perhaps be better suited for other types of buildings or climates than the techniques investigated here. Moreover, this report could be extended to include the rest of Australia, and the vast climates that exist in it, and examine whether or not it would be viable for the whole country, as bioclimatic techniques have the potential to reduce air-conditioning usage and energy consumption everywhere, with proper investigation into each area's climate so the most suitable and effective design techniques are identified.

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PART D EXAMINATION

The examination is set externally by QCAA and covers both Units 3 and 4 of the syllabus. The examination accounts for 50% of the total assessment in physics and is delivered in two 90 minute papers which could be on the same day (morning and afternoon).

The QCAA defines an examination as a supervised test that assesses the application of a range of cognitions to one or more provided items such as questions, scenarios and/or problems. Students complete their responses individually, under supervision and in a set time.

The assessment objectives are to:

- describe ideas and findings
- apply understanding
- analyse data to identify trends, patterns, relationships, limitations or uncertainty
- interpret evidence to draw conclusions based on analysis.

The following table outlines key information about each exam paper. Look at the table carefully and make yourself familiar with the unique features of each paper.

Examination	Key information
Question types	• Questions may ask students to respond using: • multiple choice • single-word answers • sentences and paragraphs • calculating using algorithms • interpreting using graphs, tables or diagrams • responding to unseen data and/or stimulus
Syllabus coverage	• Units 3 and 4
Conditions	• perusal (reading) time: 5 minutes • writing time: 90 minutes
Equipment	• QCAA approved graphics or scientific calculator permitted • approved writing equipment • seen formula and data booklet provided
Marks	constitutes 50% of total assessment

Careful and thorough preparation for the examination should help reduce some of the anxiety and stress you may experience in the lead-up to this assessment. Many students feel that their performance in the examination, as in all assessments, is what will define them and determine their future career paths.

Remember, no matter how you feel about your performance, there is nothing you can do to change it. If you have not achieved the score that will gain you entrance into the course for your preferred career path, consider your options. Investigate different pathways to move towards your goal. Consider different courses. Seek advice from teachers and especially your careers teacher. Sometimes the path to achieve a career goal is less direct or a different career will be more suitable.

It is very common and easy for students to become 'consumed' by the demands and pressures of their final year of school. So remind yourself that there is life beyond Year 12!

This guide provides you with practical suggestions and support to prepare for the examination. The guide takes a year-long approach to your preparation that includes:

- consolidating learning—effective learning routines and strategies for use throughout the year
- revising and practising—study practices and strategies for the weeks leading up to the examination
- sitting the exam—strategies and hints for tackling the examination
- after the exam—some considerations.

Engage in positive 'self-talk'. You know more than you think you know.

1.19 Examination preparation

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- prepare yourself to successfully complete the examination.

As you work through the course material during the year, it is vital that you take detailed notes from classwork and homework. These notes will be the foundation of your revision and summary notes, so they should:

- cover all aspects of the syllabus
- focus on key concepts
- give greater emphasis to larger topics than minor ones
- include examples and applications
- include definitions of key terms
- include questions with a range of cognitive verbs, and suitable answers (that have been checked)
- be legible!

CONSOLIDATING LEARNING

Begin study early. It is easy to procrastinate and then find yourself rushing to revise and study at the last minute. Just-in-time is not a recipe for success. Learning is more effective if it is spread over a long period instead of a last-minute cram.

Learning requires discipline over the duration of the course. Repetitive and frequent revision of the course material helps to reinforce and deepen understanding and helps embed learning in your long-term memory. Studying and revising can be overwhelming. Revise manageable chunks by dividing your work into smaller sections or topics.

During the year, get into the habit of revising completed sections of the course. The revision may be done, for example, at the end of a week, a topic, a chapter or at intervals that best suit you. Revise work from earlier in the year on a regular basis. Ask your teacher for copies of any past exams you have done and use the answer/marking scheme to help you revise. It is easy to forget information if you don't keep reminding yourself.

> Time management is important.
> Use your study time effectively.
> Use your leisure time effectively.

There are a number of revision strategies you might use. Identify your own study strengths—what works best for you—then make effective use of these strengths.

Following are some effective learning routines and strategies for use throughout the year.

1 Your teacher is a physics expert. They are an excellent resource and should be the first person you consult for support and help. Seek help during class if you are struggling to understand concepts. If you encounter problems out of class time, it is a good idea to write down areas that you are struggling with and consult your teacher at the next opportunity. Remember to pinpoint specific concepts or questions. Ask your teacher to re-explain concepts and ask for more material and/or questions for practice.

2 Make your own flash cards. Dedicate each card to a particular idea that could include:

- definitions—key term on one side with the definition on the back
- diagrams—diagram on one side with a brief explanation on the back
- equations and formulas—formula on one side with a worked example on the back
- graphs—graph on one side with a summary of results on the back
- questions—question on one side with the answer on the back.

Use the cards to test yourself. Ask friends or family to test you. Periodically reading the cards reinforces learning and entrenches concepts in long-term memory

(Figure 1.19.1). Flash cards are an excellent tool for subject matter that must be remembered.

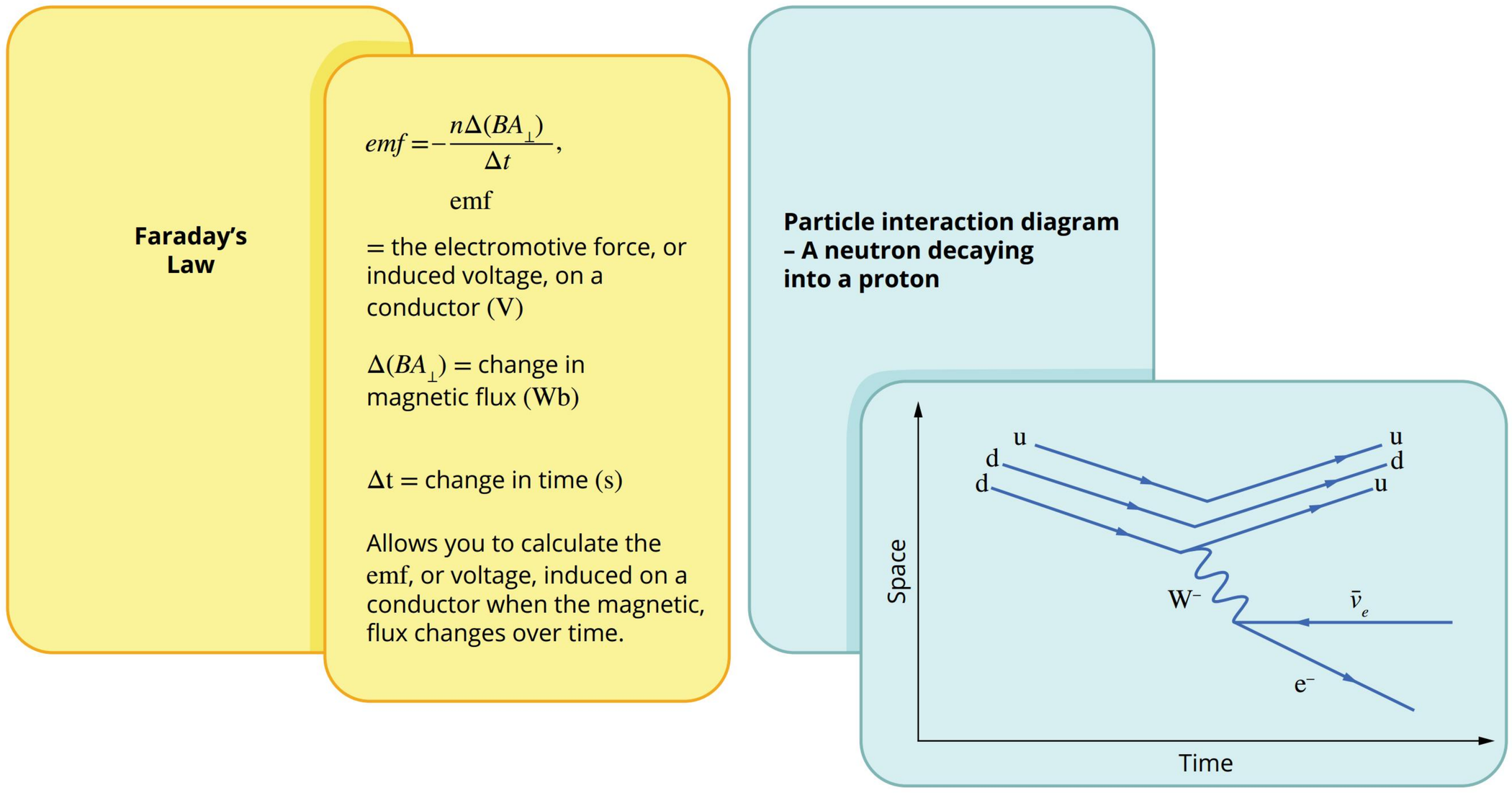


FIGURE 1.19.1 Flash cards are an excellent tool for remembering and testing yourself on factual material.

3 Trigger words. Write down the key words associated with a topic or theme. Trigger words are useful in helping to generate other related words and ideas. This approach is helpful in preparing everything from quick drafts to questions and concept maps to summarising whole topics.

4 Diagrams are useful memory triggers—draw first, label and explain second!

5 Test yourself. Complete as many questions as possible to test your learning. Handwrite (not type) your answers. Writing is more valuable practice than just thinking about your answer. Writing is a good way to memorise material. Remember, you will need to be able to write for 90 minutes in the allocated writing time in the exam and your writing must remain legible.

6 Summary notes. Consider your preferred learning style and take advantage of it to make revision notes. Summaries help you identify essential concepts and reinforce learning. Keep in mind that any study notes you make are most effective when they are:

- clear
- to the point
- uncluttered.

Some techniques you may apply to create useful summaries include:

- highlighting or underlining important points as you read your notes or text
- creating headings or appropriate structures under which to organise ideas eg. under each syllabus bullet point
- using labelled diagrams to summarise concepts
- creating tables to make comparisons (e.g. causes/effects, for/against)
- creating summary sheets
- using boxes, circles and colour to highlight points on your summary sheets
- using mnemonic devices or acronyms to remember key points; for example, 'ROYGBIV' or 'Richard Of York Gave Battle In Vain' gives the visible spectrum in order of increasing frequency.

- compiling a glossary of new terms. Write the textbook version and then in your own words. This helps you remember new terms
- employing mind maps or concept maps to organise key information (Figure 1.19.2).

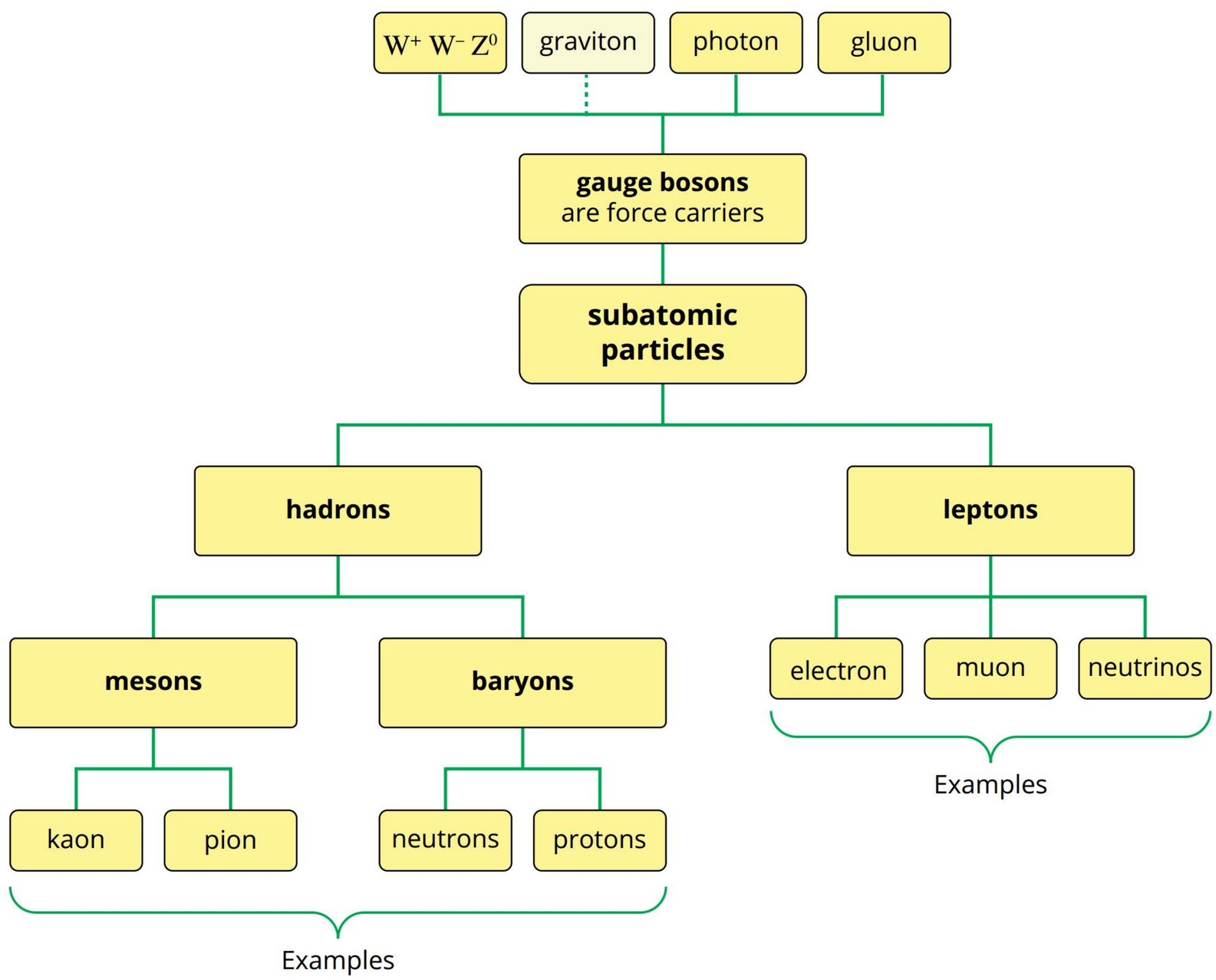


FIGURE 1.19.2 Creating visual representations in the form of concept maps is an effective revision and study tool.

7 Use chapter and module openers and module review summaries as a checklist for the key ideas in a chapter.
   - Tick those with which you feel confident.
   - Highlight those you need to revisit.
   - Reread relevant sections of text.
   - Rewrite notes, definitions or equations that you need to consolidate.

8 Form a study group with friends. The group can meet face-to-face or online. Discuss and explain key points to each other. If you are struggling with a difficult concept, try to teach it to a friend. You cannot explain something to another person until you have it clear in your own mind. Teaching and explaining to someone else makes it clearer to you.

9 Complete lots of practice questions. Write down your answers so that you get practice expressing yourself. Verbalising or thinking the answer is not the same and your responses may not always come out in writing how you intend unless you have plenty of practice. Check your answers with the study group, against a reliable source and with your teacher. Make sure the answers are correct and try to improve your answers to a higher level. Try allocating marks to your own answers.

10 Familiarise yourself with the data booklet. In the exam, you have access to the data booklet. Make sure that you use the data booklet throughout the year, as needed, to become familiar with when and how to use it. Print yourself a copy and keep it on hand. You will use it more in some topics than others.

11 Download the glossary of cognitive verbs (general syllabuses) provided by QCAA and refer to it when responding to practice examination questions. Some examples taken from the cognitive verb list are provided in Table 1.19.3.

12 Download and complete Senior physics past papers from the QCAA website. Make sure to also download the relevant marking schemes. Keep in mind that these resources relate to the 2019 Syllabus and certain questions will no longer be relevant. In addition, some new 2025 Syllabus topics will not be represented in these exams. Your teacher will be able to explain the difference between the science understanding content of the 2019 and 2025 Syllabuses.

REVISING AND PRACTISING

In the months and weeks leading up to the exam, most if not all of the course will have been taught. Your focus should now shift to studying in preparation for the exam. You will be at an advantage if you have taken comprehensive notes throughout the year, made revision summaries, completed practice questions and generally made every effort to advance your understanding and skills.

Prepare a study timetable

Allocate time to study all the subject matter and start early. Study is work that you set yourself (e.g. summary notes, practice questions) that is independent of homework or assessment provided by your teacher. A study timetable may include daily or weekly study time for all your subjects and may specify sections of each subject to be covered. While you may not stick strictly to the timetable, it is a guide to fitting everything in and allocating equal time to different subjects. An early start might mean that you study Unit 3 at home while completing Unit 4 in class. Or perhaps, revise Unit 4 Topic 1 at home while completing Unit 4 Topic 2 in class.

This kind of planned study is similar to the way an athlete builds their ability over a time period; it is not possible to achieve to the maximum level by training for just a few weeks before the event! In addition, you will feel more comfortable in that final few weeks with large sections of study completed.

Prepare summary notes

You should have been making summary notes of subject matter throughout the year. It is now time to consolidate your learning across Units 3 and 4. Remember that different topics link with each other and it is only when a whole topic or unit is completed that these links may become apparent. The summary notes you have prepared can be collated and will serve as a summary of Units 3 and 4. These notes are best hand-written as you will need to practice expressing your ideas legibly for the examination.

List all the topics and subtopics in the syllabus, including the subject matter statements. The opening pages of each chapter in your student book will guide you. You might choose to prepare a separate table for each topic and use it to write your revision notes. The sample shown in Table 1.19.1 allows for key points, formulas and diagrams, and key terms and definitions for each topic. While this layout may suit some students, it may not suit you. Adjust the labels and organisation to best suit you. For example, you may choose to include a column for worked examples and/or sample questions.

TABLE 1.19.1 A summary of revision notes in table form

Revision notes for Unit 3: Gravity and electromagnetism			
Topic 2: Electromagnetism			
	Key points	**Formulas/diagrams**	**Key terms and definitions**
electrostatics			
magnetic field—wire			
magnetic field—solenoid			
force on a conductor			
force on a charge			
electromagnetic induction			
electromagnetic waves			

Read through your student book and class notes. Identify key sections and terms. These can be added to your revision table, for later elaboration. Reread your class notes carefully for a section of work. Once you feel you understand and remember them, put the notes aside. Without referring back to the notes, start filling in the revision table. You may need to keep referring back to your notes but avoid copying them directly. Each rereading of the notes will reinforce your learning.

Refer to additional resources if you do not understand anything. This might mean checking the student book, asking your teacher, researching online or discussing with classmates. You can keep track of problem areas by writing questions in the margin of the revision table, highlighting parts of the revision notes you do not fully understand, or keeping a separate queries sheet.

Use abbreviations and symbols, but remember that only standard symbols and abbreviations may be used in the physics exam. In order to save time and space on the revision table, you can develop your own abbreviations. Dot-point notes, visuals, tables and graphs are all useful ways of summarising information. Use these in your revision table as appropriate. It is often easier to bring to mind information in these forms than to visualise a large block of text. If you are a visual learner, it may be helpful to colour code your notes to emphasise different concepts. Rewriting notes, whether in note or visual form, helps you remember them.

In preparing the revision table, you read and reread the subject matter, so your understanding continually improves and the subject matter is learned. Practise rewriting the revision table without referring to the original one. Try making a summary of the revision table so that you focus on the essential concepts. Discuss concepts with classmates to clarify your understanding. Give the revision table to a family member and ask them to test you. These are some of the strategies that can be used to reinforce your learning. Another strategy is to 'traffic light' your work. Create a list of the subject matter for Units 3 and 4 and highlight in green the concepts you are very familiar with and for which you can answer medium to difficult questions. Highlight in orange the concepts that you understand but can only answer easy and some medium-level questions. Highlight in red the concepts for which you can only answer basic questions and need help from your teacher or peers.

Practise, practise, practise!

Remember the saying 'practise makes perfect' and complete as many test and exam papers as possible. Sitting an exam requires skill and the more practise you have in advance, the more prepared you will be. Take practice exams in the time limit allocated. Handwrite your answers to get practise at working quickly, writing your

ideas legibly and expressing yourself clearly. Exam paper practice will show you what you know, but more importantly, what you do not know and need to revise. Use the marking scheme after you have completed the paper and don't be tempted to check it for a tip or hint. If you do this, you are not training your brain to work through a thought process to find the answer.

Your teacher will likely provide a mock exam for the class – reviewing your achievement here is critical to direct your final study stages and identifying areas to work on. By reviewing where each mark is awarded in the marking scheme you will become familiar with expected responses for some of the more common questions.

Remember, the QCAA past papers (two mock exams and 2020–2025 external assessments), while useful, relate to the previous syllabus which presents concepts slightly differently to the 2025 Syllabus (e.g. notation around Faraday's law, reference to Newton's laws instead of the laws of motion, Feynman diagrams instead of particle interaction diagrams) while also not assessing the new topics added in 2025 (e.g. conservation of lepton and baryon number). Your teacher will provide direction as to which questions are slightly different in QCAA past papers and which are the 'new' topics.

SITTING THE EXAM

There will always be one more practice question or one more flash card to write but nominate your stopping point and give yourself credit for the work completed; have a good night's sleep and good breakfast on exam day. Do not cram the night before the exam, but rather reread your revision table to refresh the subject matter.

Be prepared, check your calculator battery, your pens, eraser, ruler and pencils! Use the information provided by your teacher or on the QCAA website to make sure you have approved equipment. Each year QCAA publishes an external assessment equipment list for that year's exams. This should be checked carefully each year. Table 1.19.2 lists what is usually included in the list.

TABLE 1.19.2 Approved equipment for senior physics examination (QCAA). A clear plastic container or plastic bag may be used to carry the equipment. Correction fluid/tape and erasable pens are not permitted.

black or blue pens (non-erasable)
2B pencils, sharpener and eraser (good quality) Note: 2B pencils are only required for multiple-choice questions and drawing graphs or diagrams; black or blue non-erasable pens must be used for all other written responses.
approved calculator—only calculators approved by QCAA for use in assessments are permitted; calculators must be handheld and solar- or battery-powered; scientific calculators must meet the requirements set out in the scientific calculator list or graphics calculator list and be cleared of memory before entering the assessment room
highlighters—students should not highlight their responses but may highlight stimulus or questions when permitted by the supervisor
a clear plastic ruler
water in a clear, unlabelled bottle
asthma inhaler

Double-check the date, time and place of the exam. Turn up to the exam with plenty of time to spare, a positive attitude that you now have a unique opportunity to show your mastery of senior physics. Running late will only create stress before you even get into the exam room. If you are talking with friends, it's fun to predict what questions will be on the examination, or maybe compare your favourite modern physics topic – special relativity, quantum or the standard model? Remain calm and focused as you enter the exam room.

There are some strategies to keep in mind during the exam that will improve your chances of doing well. Remember, you can only be asked about information

that is included in the course. The exam is your opportunity to showcase your knowledge of this subject.

Perusal or reading time

Every exam allocates time for you to look over the exam paper - 5 minutes for senior physics. You are not permitted to pick up pens, pencils or highlighters at all during this time, not even to write your identification on the answer booklet. Use this time wisely as it is valuable for you to get an overview of the paper.

- Check through the entire paper quickly. Alert the supervisor if pages are missing/ incomplete as per exam instructions.
- Carefully read the instructions and reread them.
- Plan how much time you will allocate to different sections of the paper.
- Decide in what order you will complete the questions, i.e. perhaps do the easy questions first so you have more time to complete the harder ones.
- Start reading questions and answering them mentally.
- If a question is difficult, do not dwell on it. Move on to the next question. Sometimes another question can give clues to ones that appear difficult.
- Carefully read and reread each question. In your head, translate into your own words what you are required to do. Look carefully at questions containing unfamiliar material to determine the link to the syllabus.
- Check for measurement units that will need converting.
- Consider the marks allocated to each question. Plan to spend more time on questions that award more marks.
- Identify the extra space and second copies of diagrams at the end of the paper; you will use these if you need to re-do a question.
- Supervisors cannot respond if you think a question is written incorrectly or contains an error. Complete the paper as best you can and identify your concern at the end of working time.

Writing time

Commence writing as soon as you are permitted. Keep in mind the following strategies.

Read and reread questions carefully

If you find it helpful, underline/circle key words in the question. This can be a useful strategy in identifying the focus of the question and giving direction about what is required in your answer (e.g. cognitive verb(s)). For questions with an introductory stem and parts, read the whole question before starting to write your answer. Otherwise, you may write answers for the first part that belong to later parts. Sometimes the information in one part of a question will provide a hint for another part.

Show your working

Show all the steps you took to reach your solution on questions involving calculations (i.e. your working). While there may be an error in one part of the calculation, you may still score some marks for correct method. Remember to always include the correct units in answers and to correctly label all graphs (x and y axes, title, units). If you do work that you think is incorrect, simply draw a single diagonal line through the response and write your answer again. If you are using the additional pages provided at the back of the exam paper, do not forget to direct the assessor to the additional page number and indicate on your response which question it refers to.

Working with data

When a question includes data presented in a graph, read the labels and units on the axes and understand the relationship shown by the graph. The title of the graph will assist with this. Use a ruler for reading graphical data accurately.

When looking at tables, read the headings of rows and columns carefully so you can understand the content of the table. They usually contain symbols and units of the data. Refer to the data booklet where appropriate. You should include the proper units for each number where appropriate. If you keep track of units as you perform your calculations, it can help ensure that you express answers in terms of the proper units. Depending on the exam question, it is often possible to lose points if the units are wrong or are missing from the answer. The format of many calculating questions will provide a blank answer box (often with units) so don't forget to re-write your final answer there.

Answer all questions

An unanswered question cannot possibly earn you any marks. It is better to make an intelligent guess that might earn some marks than not answer at all. Remember that a diagram may gain marks. When you have completed an answer, reread the question. Check that you have addressed the actual question and all parts of it. An answer that includes correct information but does not answer the question will not earn any marks. Many short response questions are divided into parts a, b, c and d, where each part may have a different cognitive verb and require a different type of response. Credit for each part is awarded independently, so you should attempt to solve each part. For example, you may receive no credit for your answer to part a, but still receive full credit for part b, c or d. If the answer to a later part of a question depends on the answer to an earlier part, you may still be able to receive full credit for the later part, even if your earlier answer is wrong (known as 'carried error').

Interpret and answer the question using the cognitive verb

Provide accurate information that addresses the question to attract a mark. A key aspect of this is to identify and understand the cognitive verb used in the question. Cognitive verbs indicate the type of thinking and response required and are described in the QCAA 'Glossary of cognitive verbs- general syllabuses' document. Verbs like 'explain', 'compare' and 'analyse' tell you what you are expected to do (refer to Table 1.19.3).

The questions in your student book have been written using cognitive verbs from the syllabus, so you should be familiar with the style of questioning and will have had practice at interpreting questions that use these cognitive verbs. Make sure your answers address all parts of the question.

TABLE 1.19.3 Some examples of types of responses linked to verbs. Refer to Glossary of Cognitive Verbs (QCAA).

Cognitive verb	Thinking/response
analyse	break down a concept into its components and explain their relationships
evaluate	assess the strengths or value of something based on criteria related to physics
explain	describe aspects or parts of something in more detail
contrast	give an account of the differences between two or more things
compare	display recognition of similarities and differences, and recognise the significance of these similarities and differences
identify	recognise, state or name a fact, feature or item
calculate	determine or find (e.g. a number, answer) by using mathematical processes, showing the relevant stages in the working
describe	give an account of a situation, event, pattern or process, or of the characteristics or features of something
deduce	arrive at, reach or draw a logical conclusion from reasoning and the information given

distinguish	recognise as distinct or different; note points of difference between; make clear a difference/s between two or more concepts or items
predict	give an expected result; suggest what may happen based on available information

The following examples show that a statement can be correct but gain no marks because the desired response is not provided.

Example: ***'explain' requires more detail to make clear the 'how' and 'why'***

Question: Explain why a ball thrown in low gravity would travel further horizontally than the same ball thrown in Earth's gravity.

Answer 1: Because gravity is weaker it can travel further before it falls. ***This response does not receive full marks***

Answer 2: While the horizontal and vertical components of motion are independent, time is the variable which links the behaviour between the two components. As such, in low gravity, the vertical component of the ball's velocity will be accelerated towards the surface at a slower rate. This will cause the flight time to be extended, during which time the constant horizontal velocity will allow a greater distance to be covered, despite remaining constant. ***This response receives full marks***

Although correct, Answer 1 is not enough as the question asks for an explanation - because 'explain' asks for detail. In this case, the detail required is the independence of horizontal and vertical motion, and the relationship between time and horizontal distance. An explanation requires a statement of the physics concept but must also require the 'how and why'.

Example: ***'evaluate' requires details about the importance of a contributing factor to an outcome***

Question: Evaluate the following statement: Planets orbit the sun in elliptical orbits with the sun at the centre.

Answer 1: This is incorrect. ***This response does not receive full marks***

Answer 2: This is incorrect. According the first law of planetary motion, the sun is located at one focus of the ellipse – not the centre. ***This response receives full marks***

Although correct, Answer 1 does not contain enough information; 'evaluate' asks for criteria related to physics that has led to the decision.

Answer with clarity

There should be no room for interpretation, so be clear about what you mean to say.

Example: ***'identify' requires a specific response***

Question: Use the graph to identify the relationship between gravitational field strength and mass

Answer 1: Mass effects gravitational field strength. ***Not clear***

Answer 2: As mass increases, gravitational field strength increases linearly. ***Clear and correct for 1 mark***

Answer questions simply and concisely

Sometimes the answer to a question is simply a one-word answer (e.g. 'state' or 'identify') or a numerical reading from a graph. Providing extra information in your answer is unnecessary and can lead to irrelevant or even contradictory information. It is also an inefficient use of exam time. Where possible, use standard phrases and scientific language that neatly encapsulate meanings rather than wordy explanations. Use scientific terms and give your answers to the correct number of significant figures and with a unit. Provide only one answer to each question, never try for an each-way bet!

Use the number of lines provided in the answer booklet as a guide to how much to write. Also, use the number of marks allocated to a question or part of a question as a guide to how detailed your answer should be. Consider whether you can add

more details, a diagram, clearer explanations, or make corrections to answers. An 'identify' question may be just one mark and you provide only one word or a number with a unit. But 'compare' may be three marks because there are three aspects to the response (similarity, difference, significance, see Table 1.19.3). By noting the cognitive verbs during practice questions, you will become familiar with matching the expected responses and number of marks.

Pay attention to your spelling and write legibly. When trying to answer quickly, writing often becomes 'messy' but an assessor should not have to guess what word you have written. For example, clearly write 'flux' so that the reader doesn't identify it as 'force' or 'field'. Do not copy the question into your response as this wastes time and answer space, and does not provide an answer. Do use any scientific terms provided in the question to support your answer.

Multiple-choice questions

Multiple-choice questions are designed to make you select between very similar or opposite items. Read all options carefully. If you're unsure, start by eliminating answers you know to be incorrect. Make your final choice from the possible answers that remain. Answer every multiple-choice question, even if all you can do is guess. You should answer each multiple-choice question before you move on to the next one. You can mark a question to come back to later if you have time but you should still fill an answer before you move on. You should allow just over a minute for each question. If the question takes longer than that, take a guess and move on.

Multiple choice answers are completed by filling the bubbles on a separate answer sheet (first page of paper 1). Answers written or circled on the question booklet are not marked. Make sure that you mark your answers on the answer sheet using a 2B pencil (easy to erase if needed).

Difficult questions

If you find a question particularly difficult, skip it. Come back to it later if you have time. You should never use the 'scattershot', 'brain dump' or 'laundry list' approach, i.e. writing answers with as many terms and facts as you can, hoping that the correct one will be among them. Your answers need to be well organised and relevant; take a few moments to plan before writing longer responses.

Mental blocks

Sometimes in conditions when you are under pressure, your mind can go blank. The information is there but temporarily not available to you. Take a few deep, slow breaths. Try to visualise your notes on the revision table you created. If this does not work, move onto another question and return to this question later. Often answering a further question will jog your memory on the topic and you will be able to provide the answer on the second try. It is useful to have a system for annotating which questions need to be revisited; you may quickly write the issue which has caused the 'block' as a reminder.

Check your answers

If you have time, return to questions that you are unsure of. There is no need to check all answers if you run out of time. Reread each question when you have finished answering it. Focus on the information/answer requested and the cognitive verb in the question. These two aspects will help you to be sure that you have addressed every part of the question to the correct cognitive level.

Double check reasoning in non-numerical answers; you may have made an error that could change the meaning of your response. This is especially true when your reasoning uses several stages. An example of this would be explaining the motion of objects in special relativity, particularly in the paradoxical scenarios. Make sure you are referring to the motion of the object in the required frame of reference. With multiple observers, moving parts, and differing frames of reference it is very easy to get these mixed-up. Re-read your response carefully to ensure your explanation is worded as intended.

Never leave the exam early

Exams are generally designed to take the full writing time allocated to them. If you finish early, recheck for anything you may have missed. Check for blank pages and both sides of the page to make sure you haven't missed anything! Count the number of questions you have answered against the number listed on the front of the exam paper.

Do not leave a question blank, have a guess! No marks will be deducted for an incorrect answer but you may pick up marks for a partial response. Also, if you're unsure of a multiple-choice answer, try to eliminate one or more of the options then have a guess. You may be lucky!

AFTER THE EXAM

Once you have left the exam room, avoid talking to other students about the exam. Everyone has an opinion on their own personal performance. Listening to others can be unsettling. Whether you feel you performed well or are disappointed with your performance, it is now beyond your control. Consider writing a 'debrief' which describes the question(s) you answered best and one that you are unsure of. Remain calm and look forward to downloading the papers and marking scheme when they are available during Term 1 of the next year. It is one exam result, in one subject, in one year of your life. No matter what happens, there are plenty of career pathways to pursue.

Remember:

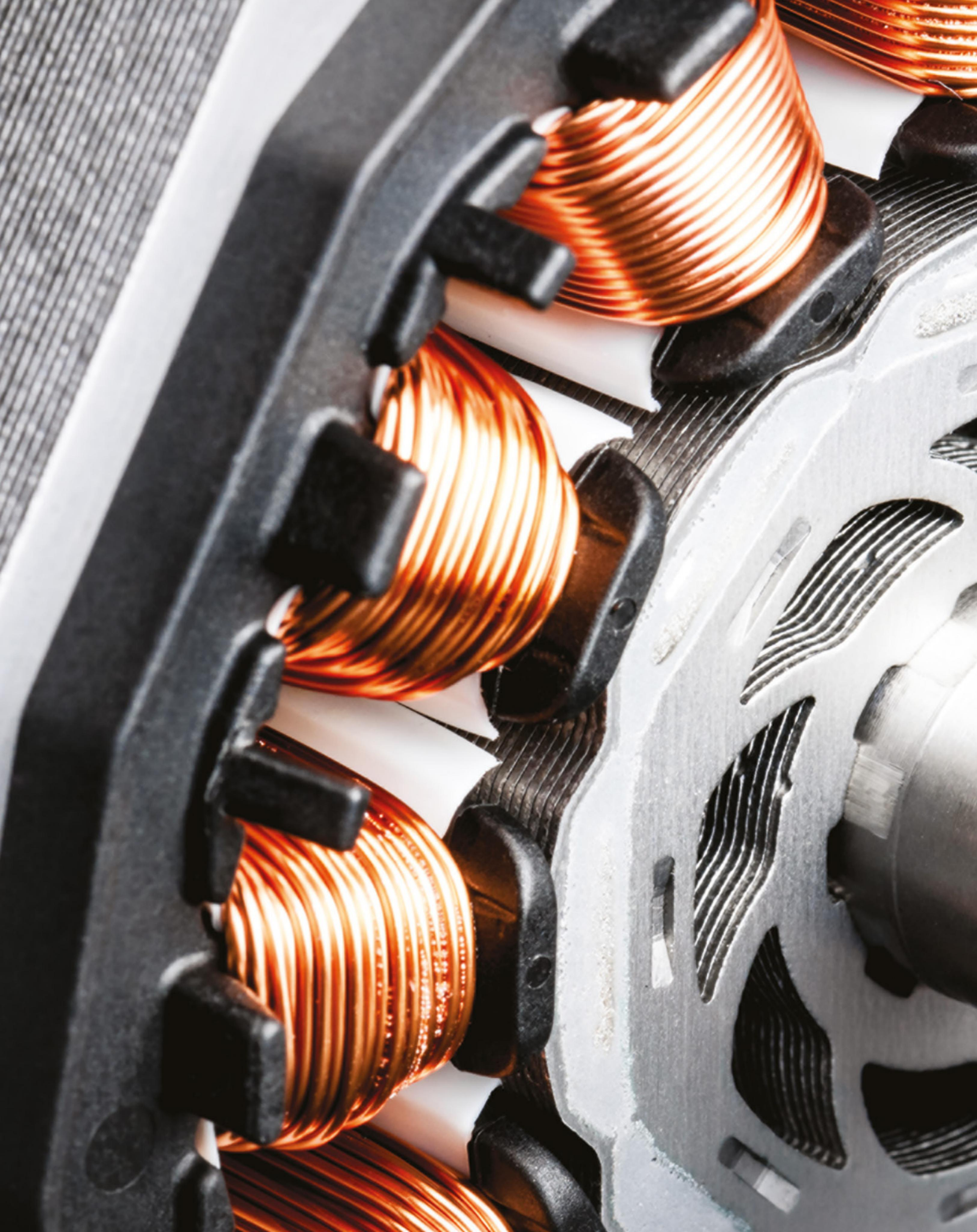
- You can only be asked about information that is included in this course. A new context may be used but it will have a link to Unit 3 or Unit 4.
- The exam is your opportunity to showcase your knowledge of this subject.

Appendix

APPENDIX 1 Quality of evidence

Quality of evidence used to form conclusion					
Weighting %	**Aspect**	**Heirarchy**	**Judged**	**Value**	
20	Relevance of Source to RQ	Highly relevant to the topic	Y	20.0	/20
		Moderately relevant			/10
		Not relevant at all			/0
30	Credibility of the Source	Peer-reviewed or from a reputable publisher	Y	30.0	/30
		Authored by an expert in the field			/15
		Lack of clear authorship or affiliation			/0
20	Currency of the Information	Recently published/updated (last 2 years)			/20
		Somewhat recent (last 5 years)			/10
		Outdated or not specified	Y	0.0	/0
30	Consistency with Existing Literature	Consistent with other credible sources	Y	30.0	/30
		Somewhat consistent			/15
		Contradictory with existing literature			/0
Judgement of Quality of Evidence			Excellent (80%)		

All of the evidence is of excellent quality aside from its currency. One source is dated from 2023, extremely current, whereas the others are from 9, 10 and 22 years ago and, for example, the house cooling technology may have improved in the time since then. The current one (2023) is a regularly produced source from a government website, however, the rest are from reports and experiments where there is otherwise limited research, additionally limiting its accuracy and its quality of evidence.



UNIT 3 Gravity and electromagnetism

TOPIC 1 Gravity and motion

TOPIC 2 Electromagnetism

Unit 3 objectives

Students will:

- describe ideas and findings about gravity and motion, and electromagnetism
- apply understanding of gravity and motion, and electromagnetism
- analyse data about gravity and motion, and electromagnetism
- interpret evidence about gravity and motion, and electromagnetism
- evaluate processes, claims and conclusions about gravity and motion, and electromagnetism
- investigate phenomena associated with gravity and motion, and electromagnetism.

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CHAPTER 02

Vectors and projectile motion

Objects in the environment often move in three-dimensional space. Every time a ball is thrown, bowled, kicked or hit in a sporting event, every time a skier or motorcyclist goes over a jump, and every time a projectile such as an arrow or artillery shell is fired, the motion can be analysed.

Chapter 6 of *Pearson Physics Queensland Units 1 & 2* introduced vectors and one dimensional motion. This chapter extends that and explores using vectors in two dimensions to analyse more complex motions.

Vectors allow motion to be divided into components at right angles (90°) to each other. For projectiles near the surface of Earth, the vertical component of motion is accelerated due to Earth's gravitational field, while the horizontal component of velocity remains constant. Projectile motion is the branch of physics that studies this kind of motion, and is applied to a wide range of sporting, gaming, military and other activities.

Syllabus subject matter

Topic 1 • Gravity and motion

PROJECTILE MOTION

- Apply vector analysis to resolve a vector into two perpendicular components. **2.1**
- Solve vector problems by resolving vectors into components, adding or subtracting the components and recombining them to determine the resultant vector. **2.1**
- Describe how horizontal and vertical components of a velocity vector are independent of each other. **2.1, 2.2**
- Solve problems involving projectile motion in the absence of drag effects using $v_y = u_y + gt$, $s_y = u_y t + \frac{1}{2}gt^2$, $v_y^2 = u_y^2 + 2gs_y$, $v_x = u_x$ and $s_x = u_x t$ **2.2**
- Interpret data relating to the horizontal distance travelled by an object projected at various angles from the horizontal. **2.2**

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2.1 Vectors in two dimensions

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- describe two-dimensional vectors in the horizontal and vertical planes
- combine vectors in two dimensions
  - graphically using a scale and a protractor
  - geometrically using trigonometry and Pythagoras' theorem
- resolve vectors into their components in two perpendicular directions using geometrical methods
- combine vector components to find a resultant vector.

In Units 1 and 2, you learnt the difference between scalars and **vectors**, and explored vectors in one dimension. When vectors are in one dimension, it is relatively simple to understand direction. However, some vectors will require a description in a two-dimensional plane. These planes could be:

- horizontal, which can be defined using north, south, east and west
- vertical, which can be defined in a number of ways including up, down, left and right.
- inclined, such as on an inclined plane (see chapter 3), and can be defined relative to the incline, for example, 'up the incline' or 'down the incline'.

Vectors require magnitude, units and direction to make sense. Some examples of vectors include **displacement**, **velocity**, **acceleration** and force. Arrows are used to represent vectors, where the length of the vector is proportional to the magnitude of the vector, and the direction of the arrow indicates the direction of the vector.

The description of the direction of these vectors is more complicated and therefore, a more detailed convention is needed for identifying the direction of a vector. There are a variety of conventions, but they all describe a direction as an **angle** from a known reference point.

HORIZONTAL PLANE

The horizontal plane is one that is looked down on from above. Examples include looking at a house plan or map placed on a desk.

For a horizontal, two-dimensional plane, two common methods are used to describe the direction of a vector: full circle (or true) bearing and quadrant bearing.

- A full circle (or true) bearing describes north as zero degrees true. This is written as 0°T. In this convention, all directions are given as a clockwise angle from north. As an example, 95°T is 95° clockwise from north.
- In a quadrant bearing, all angles are referenced from either north or south and are between 0° and 90° towards east or west. In this method, 30°T becomes N30°E, which can be read as 'from north turn 30° towards east'.

Using these two conventions, north-west (NW) would be 315°T using a full circle bearing, or N45°W using a quadrant bearing. Figure 2.1.1 demonstrates these two methods.

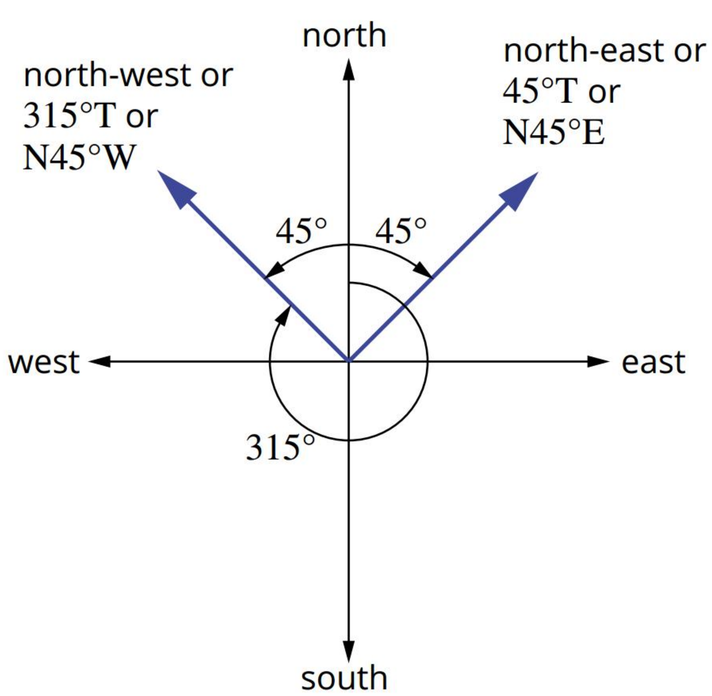


FIGURE 2.1.1 Two horizontal vector directions, viewed from above, using full circle bearings and quadrant bearings.

VERTICAL PLANE

For a vertical, two-dimensional plane the directions are referenced as vertical (upwards and downwards) or horizontal (left and right). Vectors are described compared to these directions, such as 45 degrees above the horizontal, or more

precisely with clockwise and anticlockwise. For example, a vector direction can be described as '60° clockwise from the left direction'. The same vector direction could be described as '30° anticlockwise from the upwards direction'. The opposite direction to this vector would be '60° clockwise from the right direction or 30 degrees anticlockwise from the downwards direction'. This example is illustrated in Figure 2.1.2.

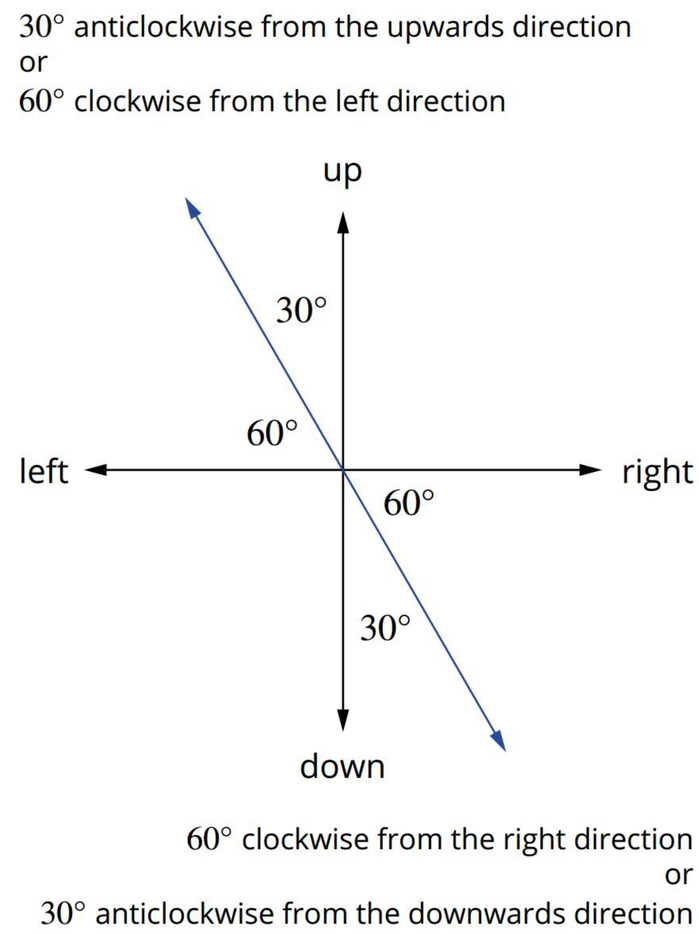
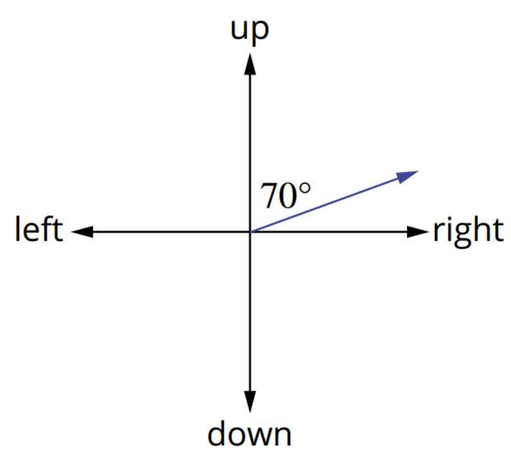


FIGURE 2.1.2 Two vectors in the vertical plane

Worked example 2.1.1

DESCRIBING TWO-DIMENSIONAL VECTORS

Describe the direction of the following vector using an appropriate method.

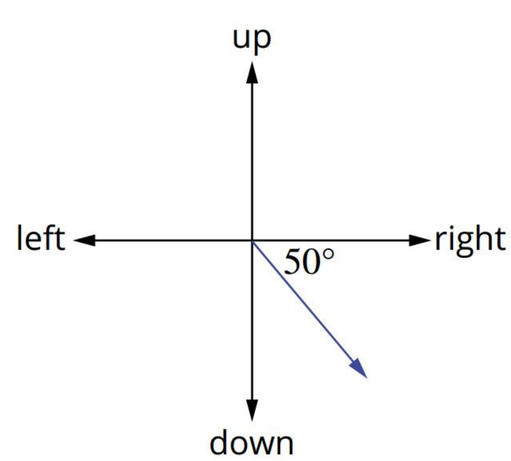


Thinking	Working
Choose the appropriate points to reference the direction of the vector. In this case using the vertical reference makes more sense, as the angle is given from the upwards direction.	The vector can be referenced to upwards direction.
Determine the angle between the reference direction and the vector.	In this example there is 70° from the upwards direction to the vector.
Determine the direction of the vector from the reference direction.	From vertically up, the vector is clockwise.
Describe the vector using the sequence: angle, clockwise or anticlockwise from the reference direction.	This vector is 70° clockwise from the upwards direction.

➤ Try yourself 2.1.1

DESCRIBING TWO-DIMENSIONAL VECTORS

Describe the direction of the following vector using an appropriate method.



DETERMINING THE RESULTANT VECTOR

In *Pearson Physics Queensland Units 1 & 2* you learnt how to add and subtract vectors in one dimension to find the resultant. Adding and subtracting vectors in two dimensions uses the same principles but requires additional geometry to **resolve** each component.

To add vectors in two dimensions, all the vectors must be in the same plane. The vectors can go in any direction within the plane, and can be separated by any angle. The examples in this section illustrate vectors in the horizontal plane, but the same strategies apply to adding vectors in the vertical plane.

The direction conventions that suit the horizontal plane best are the north, south, east and west convention, or the forwards, backwards, left and right convention (Figure 2.1.3).

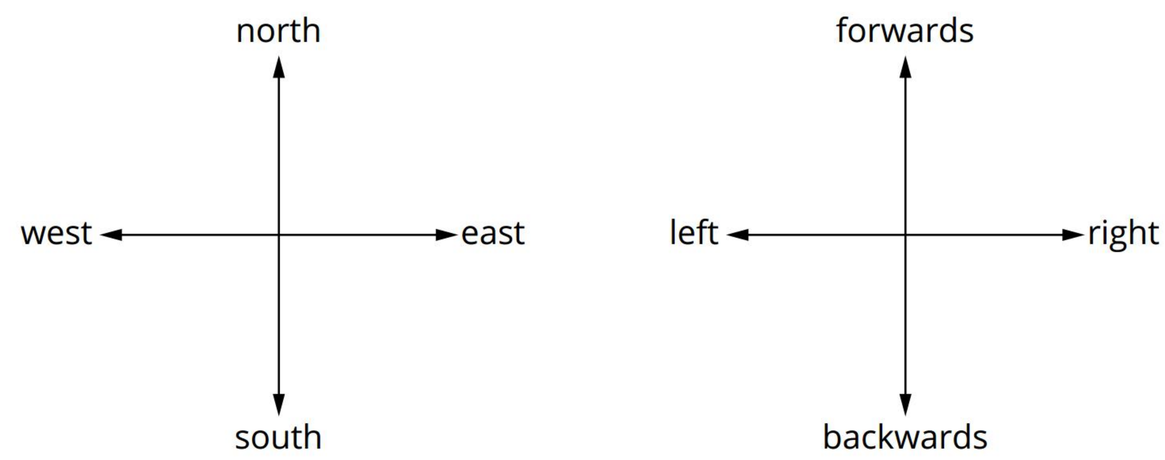


FIGURE 2.1.3 The direction conventions for the horizontal plane

Graphical methods

The magnitude and direction of a resultant vector can be determined by measuring an accurately drawn scaled vector diagram. There are two main ways to do this:

- head to tail method
- parallelogram method.

Head to tail method

To add vectors at right angles to each other using a graphical method, use an appropriate scale and then draw each vector head to tail. The resultant vector is the vector that starts at the tail of the first vector and ends at the head of the last vector. To determine the magnitude and direction of the resultant vector, measure the length of the resultant vector and compare it to the scale, then measure and describe the direction appropriately.

In Figure 2.1.4, the vectors 30.0 m east and 20.0 m south are added head to tail. The resultant vector, shown in red, is measured to be about 36 m according to the scale provided. Using a protractor, the resultant vector is measured to be in the direction 34° south of east. This represents a direction of S56°E when using quadrant bearings.

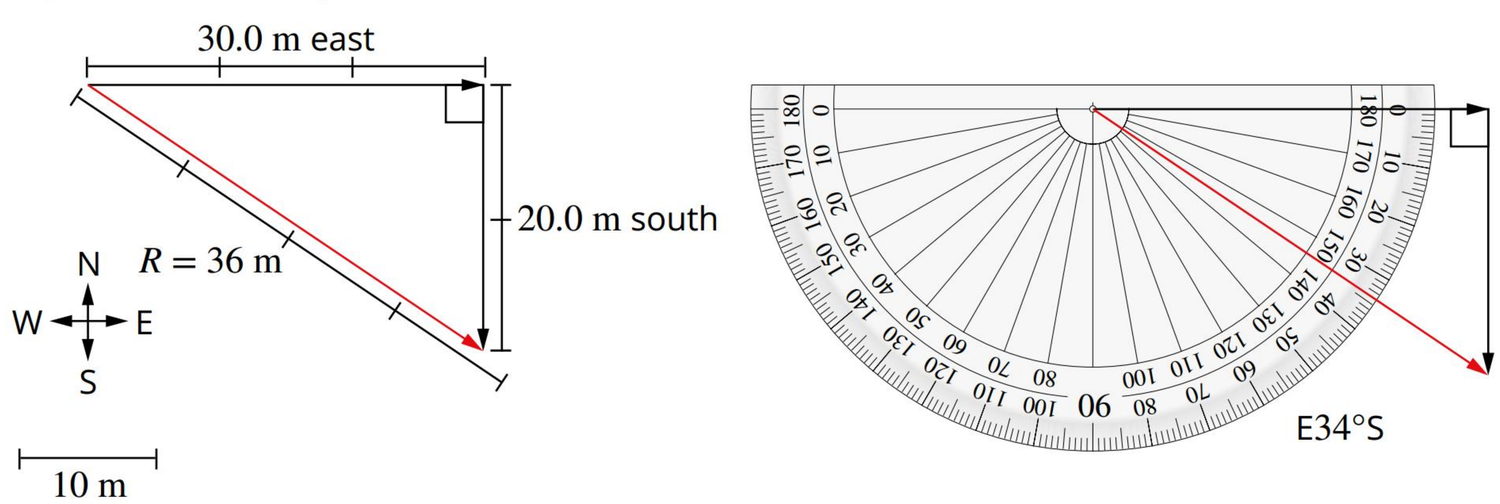


FIGURE 2.1.4 Two vectors can be added at right angles using the graphical method.

If the two vectors are at angles other than 90° to each other, the graphical method can be used to find the resultant vector. In Figure 2.1.5, the vectors 15 N east and 10 N S45°E are added head to tail. The magnitude of the resultant vector is measured to be about 23 N. The direction of the resultant vector is measured by a protractor from east to be 18° towards the south, which should be written as S72°E.

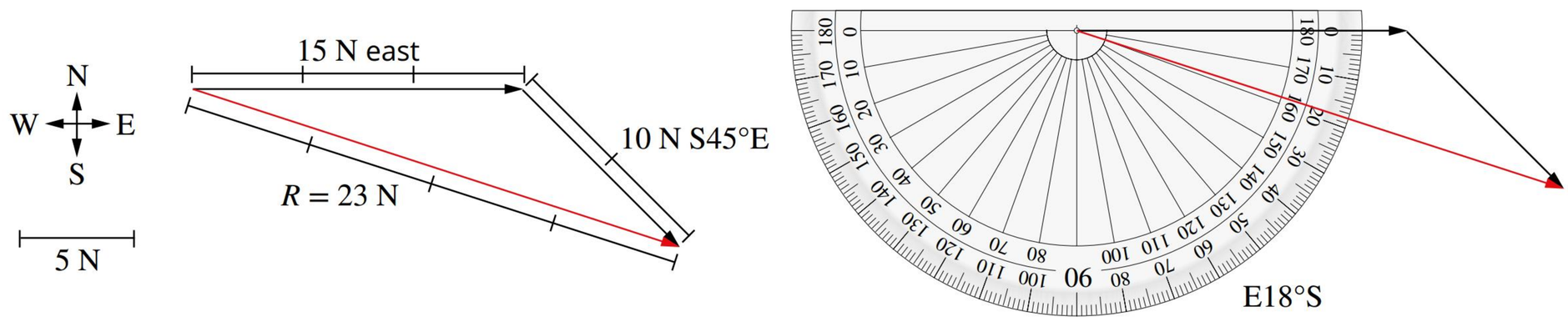


FIGURE 2.1.5 Two vectors not at right angles are added using the graphical method.

It is important to remember that the process of subtraction is identical to addition of a negative. For vectors, this means subtracting a vector is the same as adding the negative of that vector. Negatives are one of the methods used in physics to indicate direction. If a scenario involves subtraction of a vector, a vector of equal magnitude but opposite direction should be added.

A common scenario requiring subtraction of vectors is when a vector quantity changes. This could be a change in magnitude, a change in direction, or both.

Figure 2.1.6 shows the velocity vectors for an object travelling $3\,\mathrm{m\,s^{-1}}$ west and then turning and travelling $3\,\mathrm{m\,s^{-1}}$ north. The opposite of the initial velocity is drawn as $3\,\mathrm{m\,s^{-1}}$ east. Once the opposite vector is determined, this process is identical to vector addition.

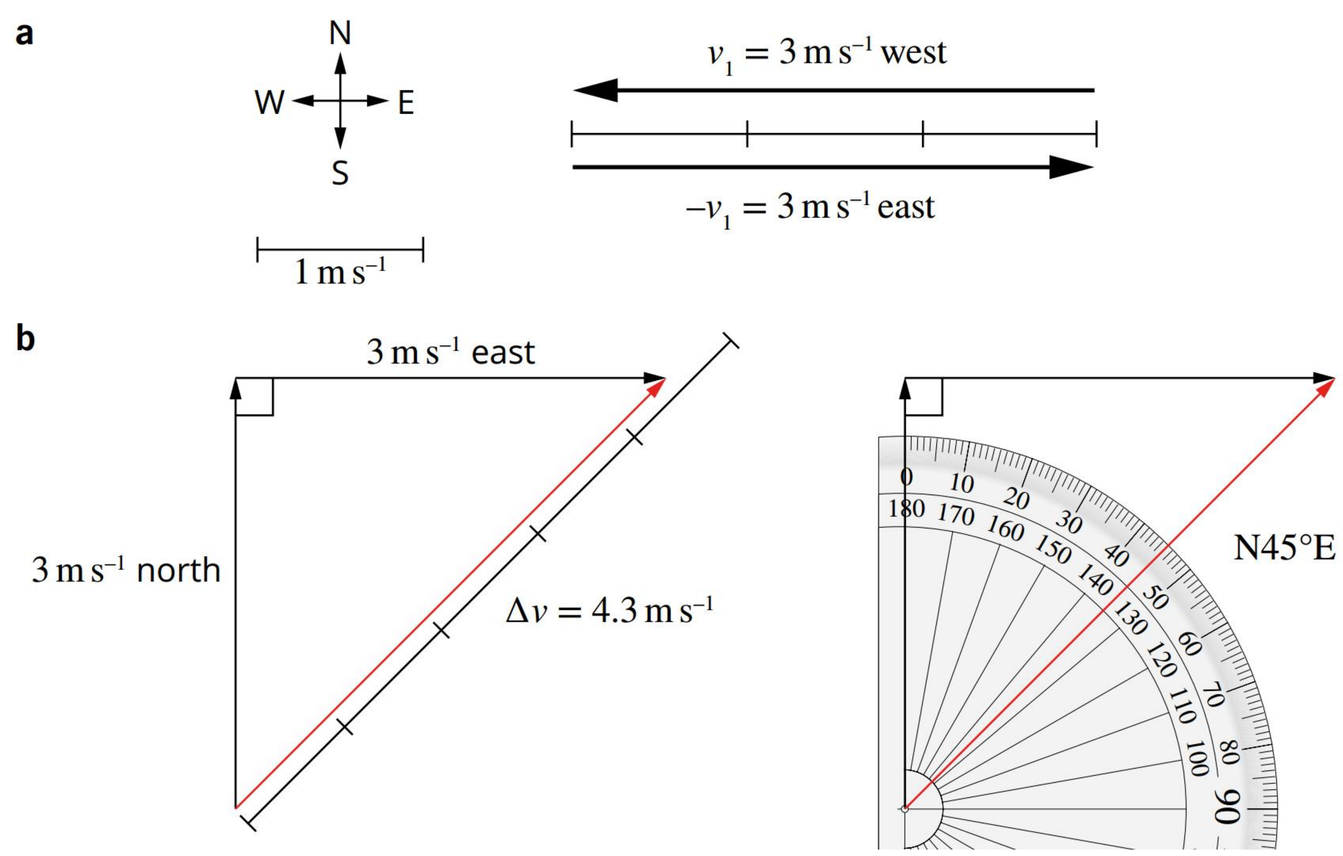


FIGURE 2.1.6 (a) The opposite of the initial velocity $3\,\mathrm{m\,s^{-1}}$ west is drawn as $3\,\mathrm{m\,s^{-1}}$ east. (b) Subtracting the two vectors at right angles, using the graphical method

When a change in a vector occurs, the magnitude and/or the direction of the vector can change.

A change in any quantity, Δx, is always given by the final value of x_f minus the initial value of x_i:

$$\Delta x = x_f - x_i$$

Parallelogram method

An alternative method for determining a resultant vector is to construct a parallelogram of vectors. In this method, the two vectors to be added are drawn tail to tail (with the opposite vector used if the scenario involves subtraction). Next, a **parallel** line is drawn for each vector as shown in Figure 2.1.7. In this figure, the parallel lines have been drawn as dotted lines. The resultant vector is drawn from the tails of the two vectors to the intersection of the dotted parallel lines. The magnitude and direction of the resultant vector are then measured using a ruler and a protractor.

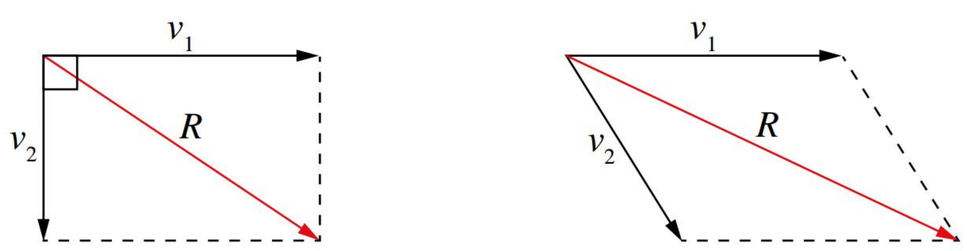


FIGURE 2.1.7 Two vectors can be added using the parallelogram of vectors method.

Pythagoras' theorem

Pythagoras' theorem is $a^2 + b^2 = c^2$, where c is the hypotenuse (the longest side), and a and b are the two shorter sides of a right-angled triangle. The hypotenuse is easily recognised as it is directly across from (opposite) the right angle of the triangle.

Trigonometric ratios

Most students learn the mnemonic SOHCAHTOA in their mathematics classes. It is often pronounced soh-cah-toa and provides a way to remember the trigonometric ratios (Figure 2.1.8):

$$\sin\theta = \frac{\text{opposite}}{\text{hypotenuse}}$$

$$\cos\theta = \frac{\text{adjacent}}{\text{hypotenuse}}$$

$$\tan\theta = \frac{\text{opposite}}{\text{adjacent}}$$

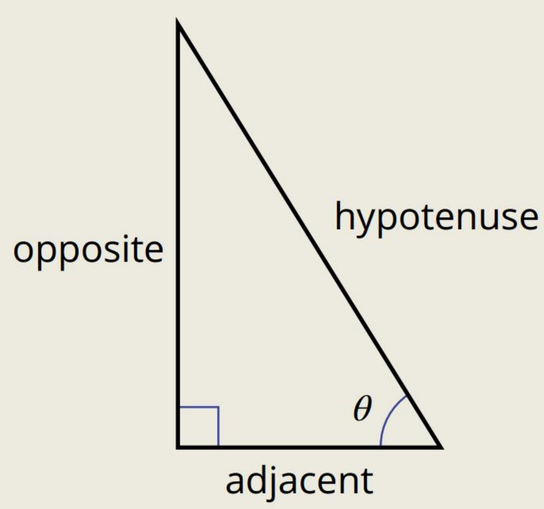
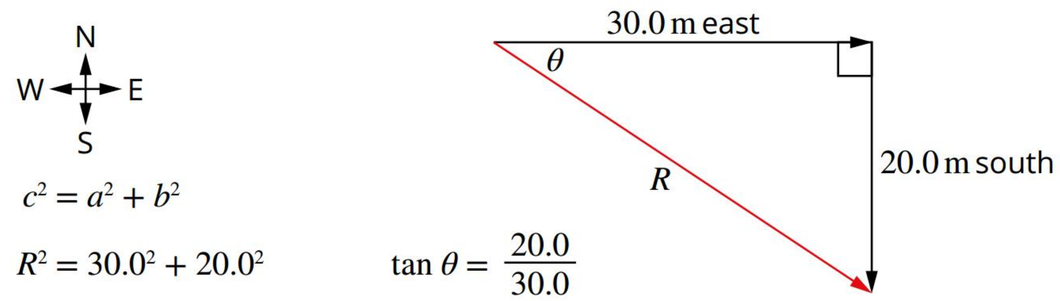


FIGURE 2.1.8 The adjacent and opposite sides of a right-angled triangle are in relation to the angle θ. The hypotenuse is the longest side of the right-angled triangle.

Geometric method

Graphical methods of adding vectors in two dimensions only give approximate results as they rely on comparing the magnitude of the resultant vector to a scale and measuring the direction with a protractor. A more accurate method is to use **Pythagoras' theorem** and **trigonometric ratios** (Figure 2.1.8). These techniques are referred to as geometric methods. Geometric methods can be used to calculate the magnitude of the vector and its direction. Pythagoras' theorem and trigonometry can only be used for finding the resultant vector of two vectors that are at right angles to each other.

In Figure 2.1.9, two vectors, 30.0 m east and 20.0 m south, are added head to tail. The resultant vector, shown in red, is calculated using Pythagoras' theorem to be 36.1 m. You can calculate the angle between the east vector and the resultant vector, using trigonometry, to be 33.7° (in the direction S56.3°E). This result is more accurate than the answer determined on page 8.



$$c^2 = a^2 + b^2$$

$$R^2 = 30.0^2 + 20.0^2$$

$$= 900 + 400$$

$$R = \sqrt{1300}$$

$$= 36.1\ \text{m}$$

$$\tan\theta = \frac{20.0}{30.0}$$

$$\theta = \tan^{-1} 0.6667$$

$$= 33.7°$$

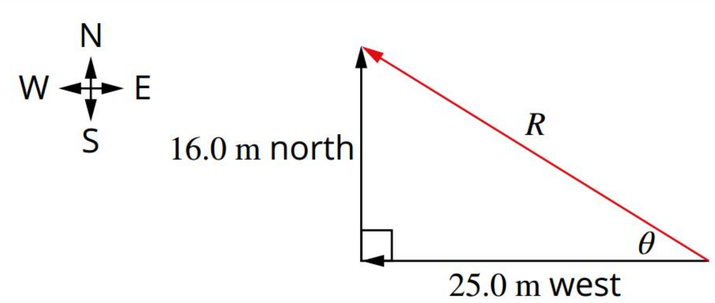
E33.7°S (or S56.3°E)

FIGURE 2.1.9 Two vectors at right angles can be added using the geometric method.

Worked example 2.1.2

ADDING VECTORS IN TWO DIMENSIONS USING GEOMETRY

Determine the resultant displacement vector that represents a child running 25.0 m west and 16.0 m north. Refer to Figure 2.1.3 for direction conventions if required.

Thinking	Working
Construct a vector diagram showing the vectors drawn head to tail. Draw the resultant vector from the tail of the first vector to the head of the second vector.	
As the two vectors to be added are at 90° to each other, apply Pythagoras' theorem to calculate the magnitude of the resultant vector.	$R^2 = 25.0^2 + 16.0^2$ $= 625 + 256$ $R = \sqrt{881}$ $= 29.7\ \text{m}$
Using trigonometry, calculate the angle from the west vector to the resultant vector.	$\tan\theta = \frac{16.0}{25.0}$ $\theta = \tan^{-1} 0.640$ $= 32.6°$
Determine the direction of the vector relative to north or south.	90° – 32.6° = 57.4° The direction is N57.4°W.
State the magnitude and direction of the resultant vector.	$R = 29.7\ \text{m}$, N57.4°W

➤ Try yourself 2.1.2

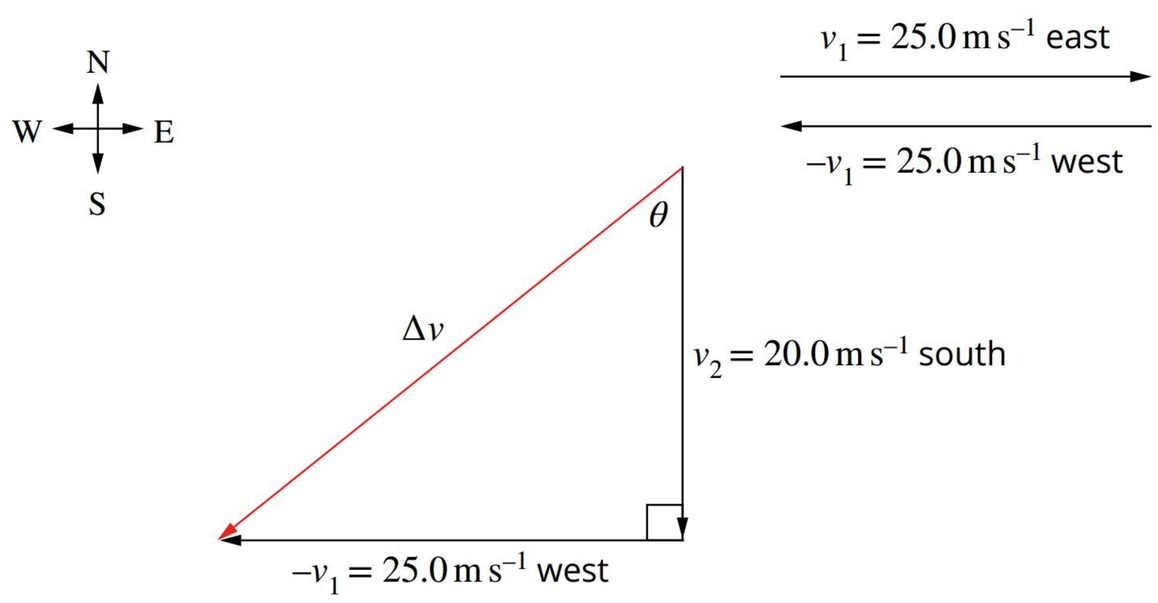
ADDING VECTORS IN TWO DIMENSIONS USING GEOMETRY

Determine the resultant force when forces of 5.0 N east and 3.0 N north act on a tree.

Refer to Figure 2.1.3 for direction conventions if required.

When subtracting vectors using the geometric method, the same additional step applies as in the graphical method: the opposite vector is added instead. The most common scenario for this is when a vector changes.

Figure 2.1.10 shows how to calculate the resultant velocity when changing from $25.0\,\text{m s}^{-1}$ east to $20.0\,\text{m s}^{-1}$ south. First, the opposite of the initial velocity is drawn as $25.0\,\text{m s}^{-1}$ west. Then, the final velocity vector is drawn head to tail with the opposite of the initial velocity vector. The resultant velocity vector, labelled Δv, is calculated using Pythagoras' theorem to be $32.0\,\text{m s}^{-1}$. The direction of the resultant vector is calculated using trigonometry to be S51.3°W. The resultant vector is $32.0\,\text{m s}^{-1}$ S51.3°W.



$$R^2 = 25.0^2 + 20.0^2 \qquad \tan\theta = \frac{25.0}{20.0}$$

$$= 625 + 400 \qquad \theta = \tan^{-1} 1.25$$

$$R = \sqrt{1025} \qquad = 51.3°$$

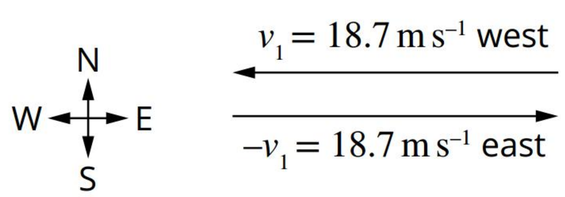
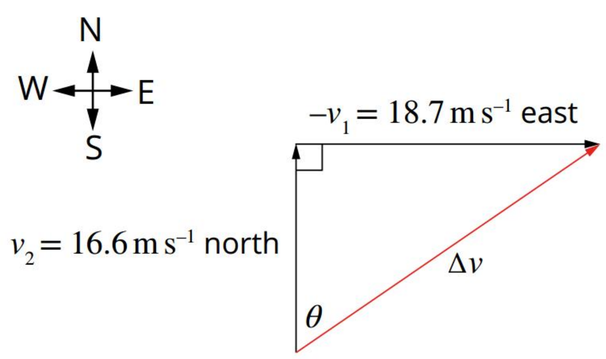
$$= 32.0\,\text{m s}^{-1} \qquad \text{S51.3°W}$$

FIGURE 2.1.10 Subtracting two vectors at right angles, using the geometric method

Worked example 2.1.3

SUBTRACTING VECTORS IN TWO DIMENSIONS USING GEOMETRY

Determine the change in velocity of Clare's scooter as she turns a corner if she approaches it at $18.7\,\text{m s}^{-1}$ west and exits at $16.6\,\text{m s}^{-1}$ north.

Thinking	Working
Recognise the initial velocity vector needs to be used in the opposite direction.	
Construct a vector diagram drawing v_2 first and then from its head draw the opposite of v_1. The change-of-velocity vector is drawn from the tail of the final velocity to the head of the opposite of the initial velocity.	

As the two vectors to be added are at 90° to each other, apply Pythagoras' theorem to calculate the magnitude of the change in velocity.	$R^2 = 16.6^2 + 18.7^2$ $= 275.56 + 349.69$ $R = \sqrt{625.25}$ $= 25.0\,\text{m s}^{-1}$
Calculate the angle from the north vector to the change-in-velocity vector.	$\tan\theta = \frac{18.7}{16.6}$ $\theta = \tan^{-1} 1.13$ $= 48.4°$
State the magnitude and direction of the change in velocity.	$\Delta v = 25.0\,\text{m s}^{-1}$ N48.4°E

➤ Try yourself 2.1.3

SUBTRACTING VECTORS IN TWO DIMENSIONS USING GEOMETRY

Determine the change in velocity of a ball as it bounces off a wall. The ball approaches at $7.0\,\text{m s}^{-1}$ south and rebounds at $6.0\,\text{m s}^{-1}$ east.

VECTOR RESOLUTION

In physics there are times when it is useful to break one vector up into two vectors that are at right angles to each other. This process is referred to as vector **resolution**, because a larger vector is broken down into two parts. For example, if a force vector is acting at an angle above the horizontal (Figure 2.1.11), this vector can be considered to consist of two independent components.

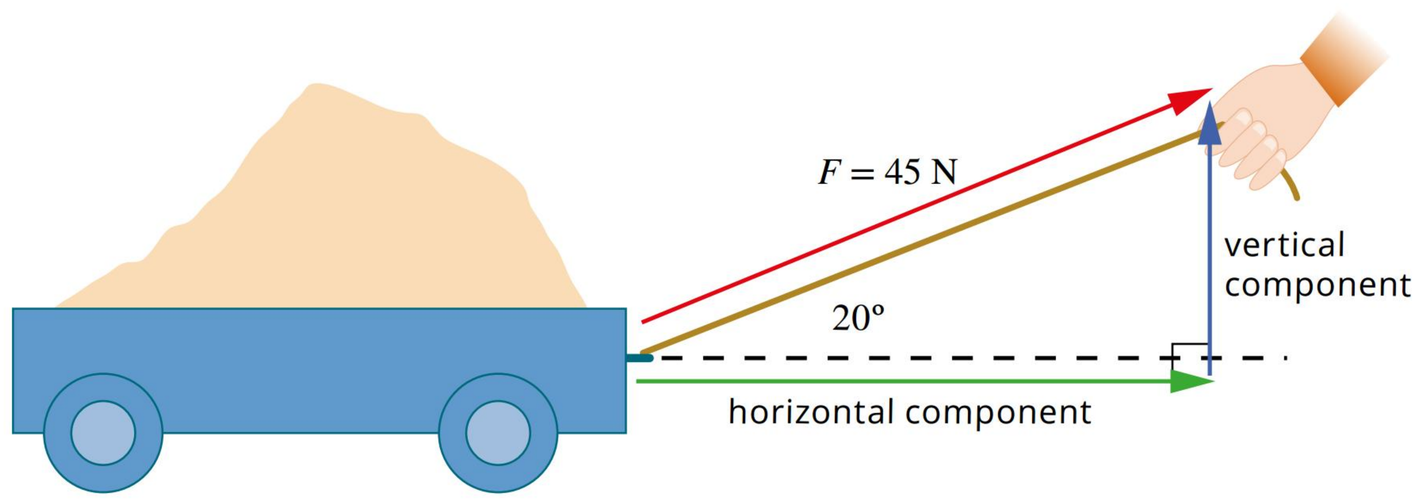


FIGURE 2.1.11 The pulling force acting on the cart has a component in the horizontal direction and a component in the vertical direction.

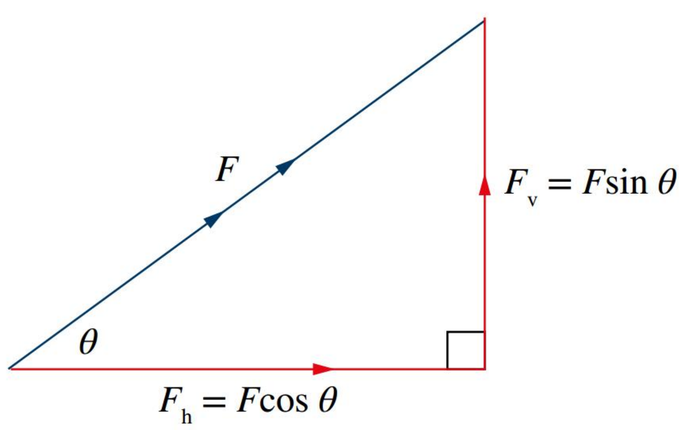


FIGURE 2.1.12 The perpendicular components (shown in red) of the original vector (shown in blue), the original vector is the hypotenuse of the triangle.

Vectors at an angle are more easily dealt with if they are broken up into perpendicular **components**; that is, two components that are at right angles to each other. These components, when added together, give the original vector. The geometric method of finding the **perpendicular** components of vectors is to construct a right-angled triangle using the original vector as the hypotenuse (Figure 2.1.12). The magnitude and direction of the components are then determined using trigonometry. A good rule to remember is that no individual component of a vector can be larger than the vector itself. In a right-angled triangle, no side is longer than the hypotenuse. The original vector must be the hypotenuse, and its components must be the other two (shorter) sides of the triangle. These two sides are the perpendicular components of the original vector.

Figure 2.1.13 shows a force vector of 50.0 N (drawn in black) acting on a box in a direction 30.0° up from the horizontal to the right. The horizontal and vertical components of this force must be found in order to complete further calculations.

> You may see the vertical component described as F_v with *v* meaning vertical, or as F_y with *y* meaning *y*-axis. Likewise, you may see the horizonal component described as F_h with *h* meaning horizontal, or F_x with *x* meaning *x*-axis.

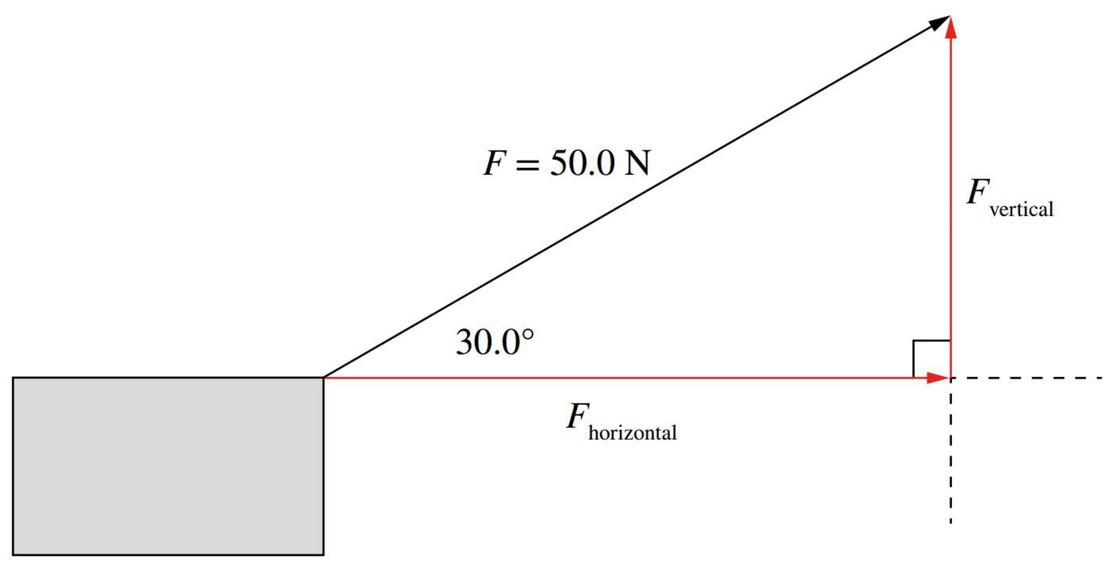


FIGURE 2.1.13 A force vector is broken into horizontal and vertical components.

The horizontal component vector is drawn from the tail of the 50.0 N vector towards the right, with its head directly below the head of the original 50.0 N vector. The vertical component vector is drawn from the head of the horizontal component to the head of the original 50.0 N vector.

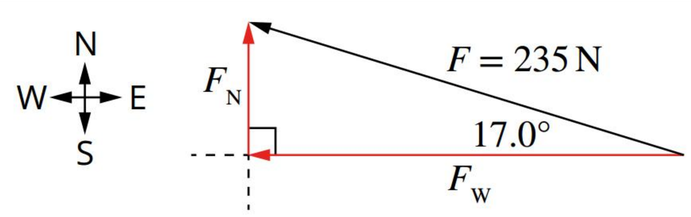
Using trigonometry, the horizontal and vertical components of the force are calculated as follows.

Horizontally:	**Vertically:**
$\cos\theta = \dfrac{\text{adjacent}}{\text{hypotenuse}}$	$\sin\theta = \dfrac{\text{opposite}}{\text{hypotenuse}}$
adj = hyp × cos θ	opp = hyp × sin θ
$F_h = 50.0 \times \cos 30.0°$	$F_v = 50.0 \times \sin 30.0°$
= 43.3 N horizontally to the right.	= 25.0 N vertically upwards

Worked example 2.1.4

CALCULATING THE PERPENDICULAR COMPONENTS OF A FORCE

Determine the perpendicular components of a 235 N force acting on a bicycle at a direction of 17.0° north of west.

Thinking	**Working**
Draw the west component of the force (F_W) from the tail of the 235 N force along the horizontal direction, then draw the north component of the force (F_N) from the head of F_W to the head of the 235 N force.	
Calculate F_W using $\cos\theta = \dfrac{\text{adjacent}}{\text{hypotenuse}}$	$\cos\theta = \dfrac{\text{adjacent}}{\text{hypotenuse}}$ adj = hyp × cos θ $F_W = 235 \times \cos 17.0°$ = 225 N west
Calculate F_N using $\sin\theta = \dfrac{\text{opposite}}{\text{hypotenuse}}$	$\sin\theta = \dfrac{\text{opposite}}{\text{hypotenuse}}$ opp = hyp × sin θ $F_N = 235 \times \sin 17.0°$ = 68.7 N north

➤ Try yourself 2.1.4

CALCULATING THE PERPENDICULAR COMPONENTS OF A FORCE

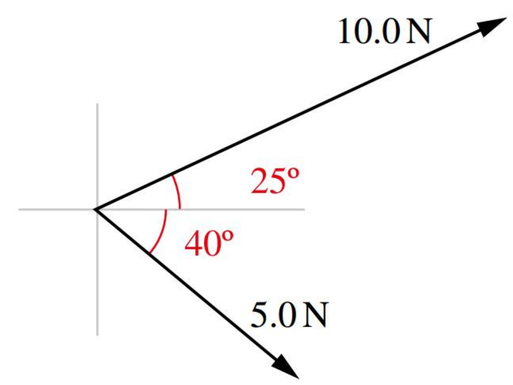
Determine the perpendicular components of a 3540 N force acting on a trolley in a direction of 26.5° anticlockwise from the left.

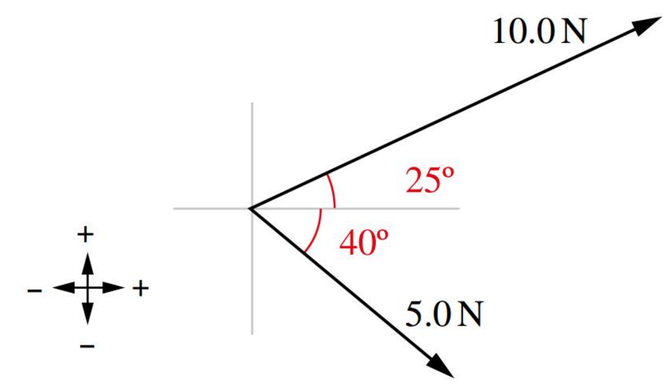
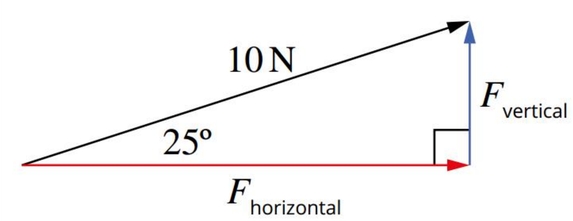
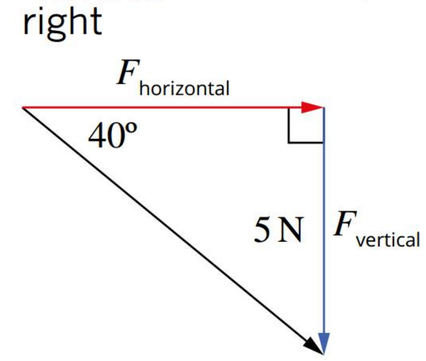
So far in this unit, vectors have generally been added and subtracted when they are at right angles to one another. Resolving vectors into perpendicular components makes it possible to add and subtract vectors that are not at right angles to one another.

Worked example 2.1.5

ADDING VECTORS THAT ARE NOT PERPENDICULAR

Resolve the two vectors in this figure into their components in the horizontal and vertical directions and then add them to find the resultant vector.



Thinking	Working
Decide on an initial sign convention for the problem, this can be done by annotating the diagram.	
Determine the vertical and horizontal components of the 10.0 N vector.	$F_{vertical} = 10.0 \sin 25.0° = 4.23$ N upwards $F_{horizontal} = 10.0 \cos 25.0° = 9.06$ N right 
Determine the vertical and horizontal components of the 5.0 N vector. The angle is below the horizontal, so write it with a negative sign.	$F_{vertical} = 5.00 \sin(-40.0°) = 3.21$ N down $= -3.21$ N upwards $F_{horizontal} = 5.00 \cos(-40.0°) = 3.83$ N right 
Add the components in each direction.	$F_{vertical} = 4.23 + (-3.21) = 1.02$ N upwards $F_{horizontal} = 9.06 + 3.83 = 12.89$ N right

Use Pythagoras' theorem to calculate the magnitude of the resultant force.	$F_{net} = \sqrt{(F_{vertical})^2 + (F_{horizontal})^2}$ $= \sqrt{1.02^2 + 12.89^2}$ $= 13\,N$
Use trigonometry to calculate the angle of the resultant force vector.	$\theta = \tan^{-1}\left(\frac{1.02}{12.89}\right) = 4.5°$ The resultant force is 13 N right, 4.5° up (or 13 N at 4.5° to the horizontal).

➤ Try yourself 2.1.5

ADDING VECTORS THAT ARE NOT PERPENDICULAR

Calculate the sum of a displacement of 20.0 km north and a displacement of 14.0 km N33.0°E.

2.1 Review

SUMMARY

- Vectors in the horizontal plane can be described using a full circle bearing or a quadrant bearing.
- Vectors in the vertical plane can be described using angles measured clockwise and anticlockwise from the vertical or horizontal.
- To combine vectors, they must lie in the same plane.
- Vectors can be added graphically with a scale and a protractor.
- An alternate method of adding vectors is to construct a parallelogram of vectors.
- Perpendicular vectors can be added using Pythagoras' theorem and trigonometry.
- To find the difference between, or the change in, vectors, subtract the initial vector from the final vector.
- Vectors are subtracted by adding the negative, or opposite, of a vector.
- Vectors can be resolved into two perpendicular components using trigonometry. These can be horizontal (x) and vertical (y) or in two other named directions, such as north and east.
- Components of different vectors in the same direction can be added or subtracted.
- Perpendicular vector components can be recombined to find a resultant vector.

2.1 Review *continued*

KEY QUESTIONS

Describe

1 Identify two things needed to describe the direction of a two-dimensional vector.

2 State another way of describing the direction 270°T.

3 Describe, using a number and the appropriate unit, the resultant force acting on a book on a chair. The book is acted on by a 20.0 N force downwards and a 20.0 N force upwards, as well as a 10.0 N force towards the back of the chair from someone pushing on it and a 10.0 N force forwards on the book from the back of the chair it is sitting on.

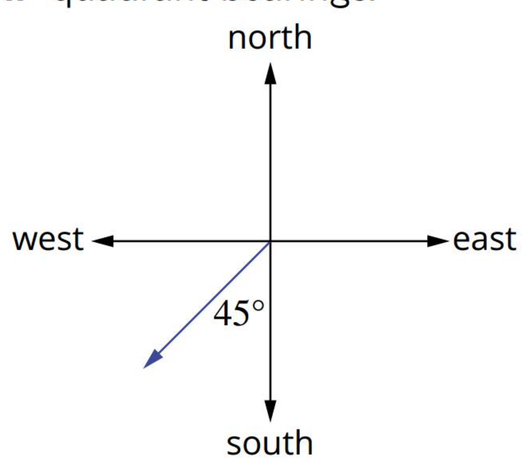
Apply

4 Describe the following vectors using:

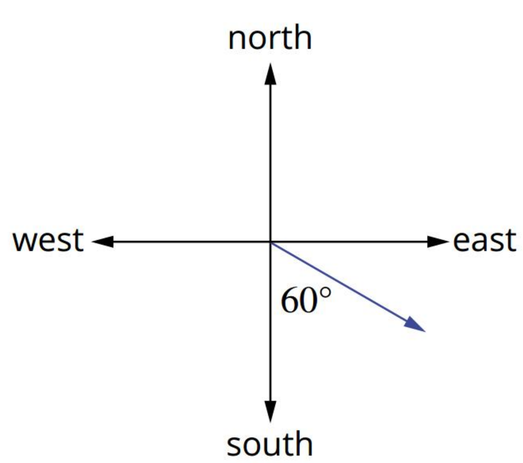
i full circle bearings

ii quadrant bearings.

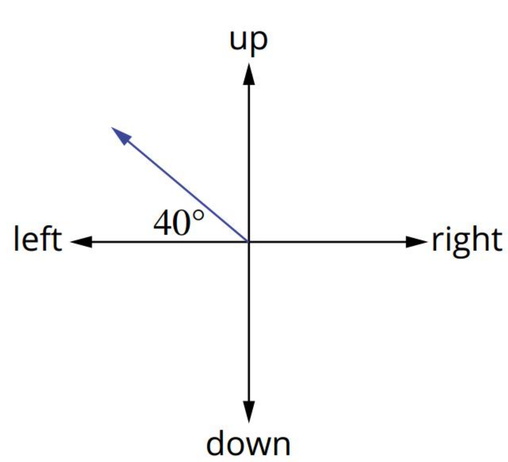
a



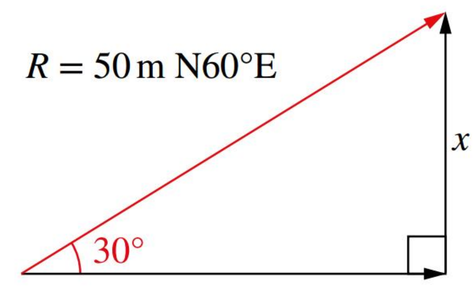
b



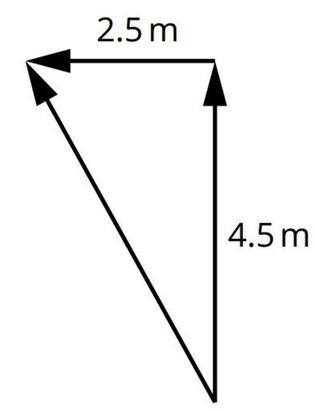
5 Describe the following vector using appropriate conventions.



6 Calculate the value of x in this figure.



7 Calculate the magnitude and direction of the resultant vector in this figure.



Analyse

8 Calculate the total distance travelled, d, and the displacement, s, if David walks 210.0 km east and then turns right and walks 87.0 km south.

9 Calculate the resultant force when a force of 27 N west is subtracted from a force of 18 N north.

10 Calculate the change in the velocity of a jet that makes a turn after taking off, changing its velocity from 345 m s^{-1} south to 406 m s^{-1} west.

11 Calculate the change in the velocity of a golf ball that Yvette hits and, when it strikes a tree, changes its velocity from 42.0 m s^{-1} east to 42.0 m s^{-1} north.

12 Zehn walks 47.0 m in the direction of S66.3°E across a hockey field. Calculate the components of their displacement.

13 Calculate the horizontal and vertical components of a 30.00 N force that is applied along a rope at 60.0° to the horizontal and used to drag an object across a yard.

14 Calculate the horizontal and vertical components of the following force vectors acting on the same object and add them to find the resultant force acting on the object: 28 N at 18° to the horizontal and 17 N at 168° to the horizontal (that is, left and slightly upwards if using the convention that right is the positive direction).

2.2 Projectile motion

BY THE END OF THIS MODULE YOU SHOULD BE ABLE TO:

- describe the interaction of acceleration and velocity in projectile motion
- understand that the vertical component of motion and the horizontal component of motion are independent of each other
- resolve projectile motion into vectors in the horizontal and vertical directions
- complete calculations of distances, heights and times for projectile motion
- interpret data relating to the horizontal distance travelled by an object projected at various angles from the horizontal.

INVESTIGATING MOVEMENT IN TWO DIMENSIONS

Analysing the flight of a ball, or any object in flight, involves considering the movement of the object in both the horizontal and the vertical directions. For example, consider the bouncing ball in Figure 2.2.1. The ball is bouncing up and down as well as moving sideways. The constant horizontal motion compared to the changing vertical motion in this figure demonstrates a significant point about projectile motion: the horizontal and vertical components of velocity are independent. This point is explored further below.

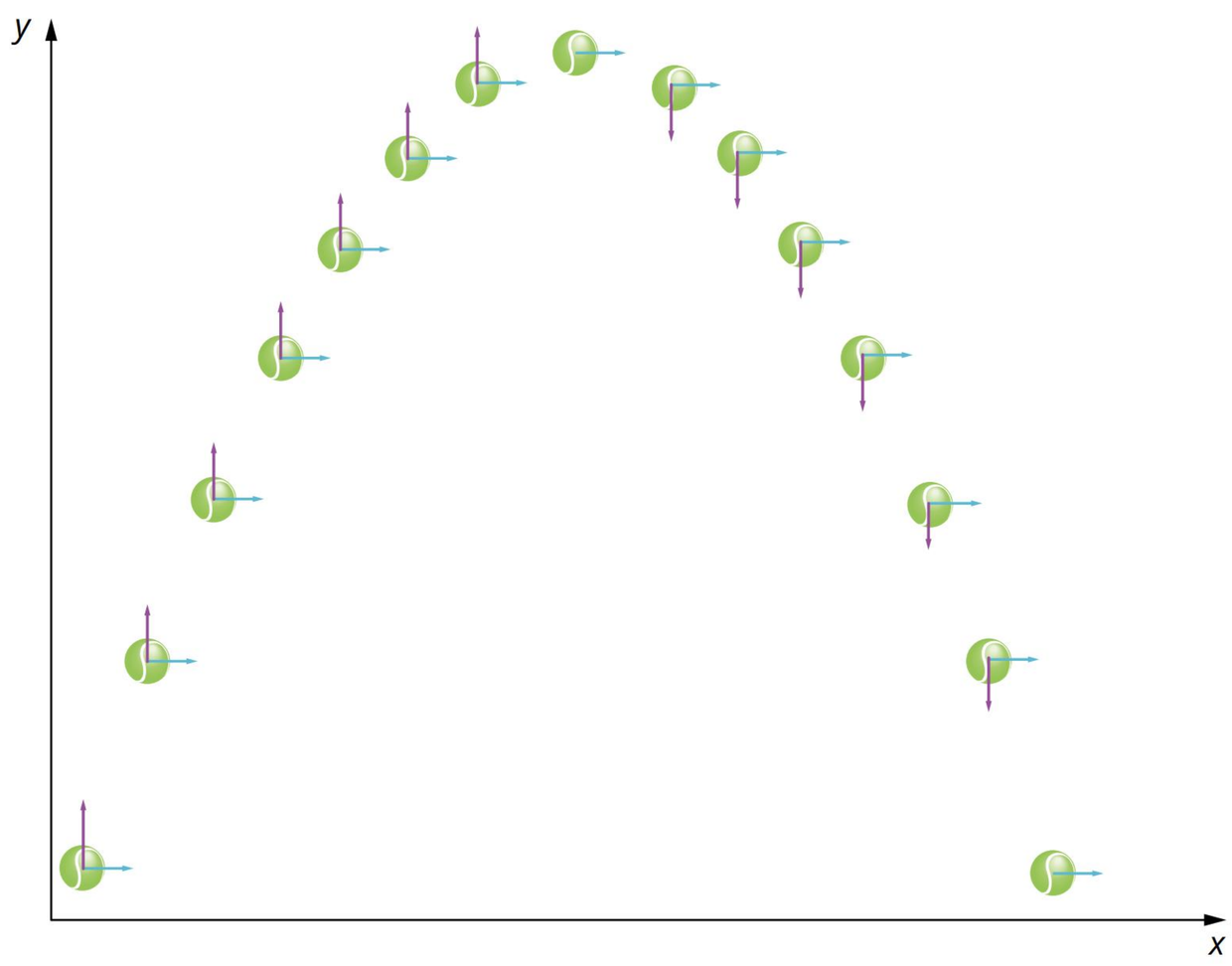


FIGURE 2.2.1 An annotated analysis of a bouncing ball showing velocity vectors at each point. The horizontal velocity is constant. The vertical velocity constantly decreases as the ball rises, becoming negative as the ball starts to fall.

Figure 2.2.2 shows the horizontal displacement (a) and the vertical displacement (b) of the ball from Figure 2.2.1, taking the ball's starting position as the origin. As the ball bounces towards the right, the horizontal position increases. Height on the vertical position graph symmetrically increases as the ball rises and decreases as it falls.

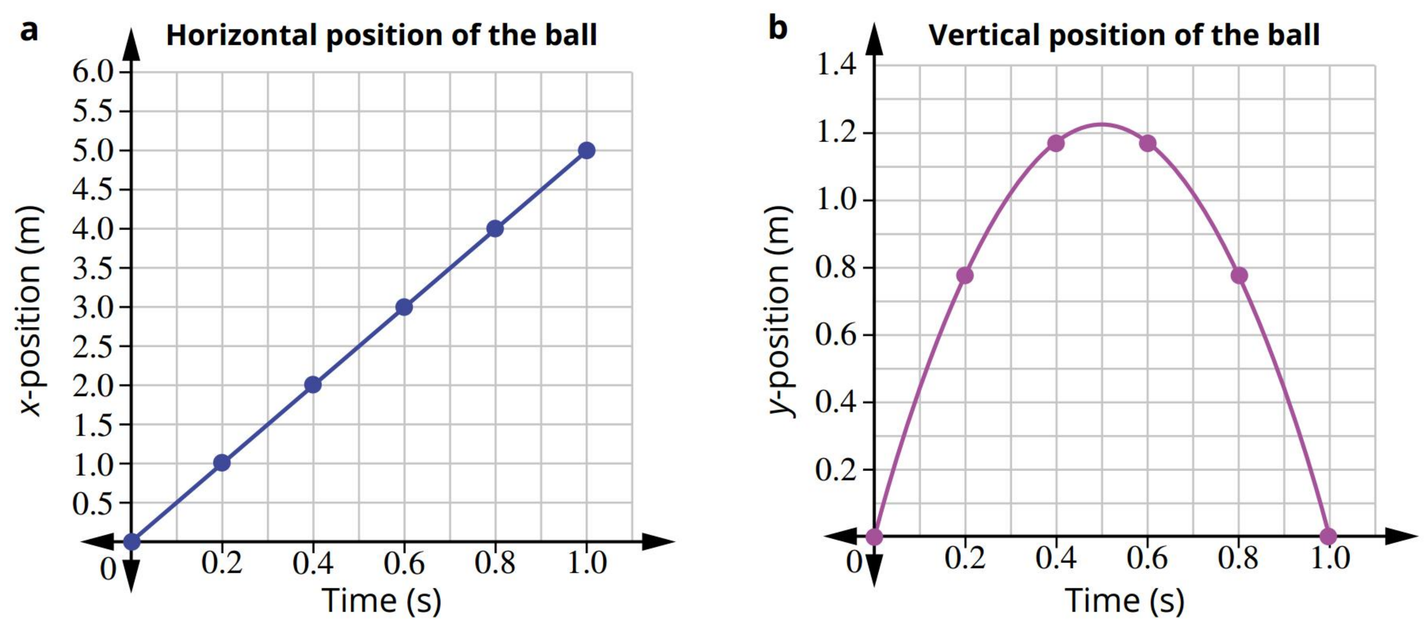


FIGURE 2.2.2 Graphs of the horizontal (a) and vertical (b) displacement of the ball from the origin

The graphs of the horizontal position of the ball (Figure 2.2.2a) and the vertical position of the ball (Figure 2.2.2b) are quite different. These differences are highlighted below.

Horizontally:

- The distance from the origin increases as the ball moves away from the origin.
- The graph is a straight line with a regular interval between each point.
- The constant gradient indicates that the velocity of the ball is constant. There is no acceleration in the horizontal direction, indicating there is no force.

Vertically:

- The distance from the origin increases as the ball bounces higher, and then decreases as the ball returns to the ground.
- The graph is roughly parabolic in shape with a changing interval between each point: the points on the graph are closer together near the top of the bounce.
- The changing gradient indicates that the velocity is changing. The ball is accelerating, indicating it is experiencing a force.

Velocity–time graphs of horizontal and vertical motion can be used to confirm these conclusions and determine the size and direction of the acceleration affecting the ball in the vertical direction (Figure 2.2.3).

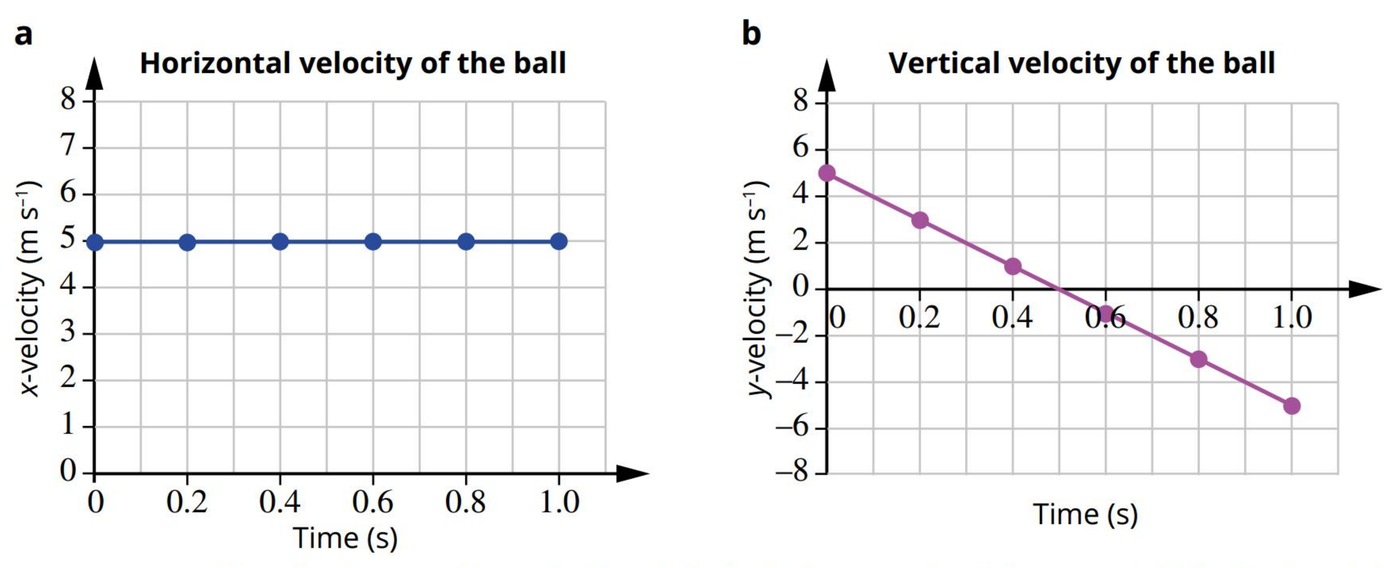


FIGURE 2.2.3 Graphs showing the velocity of the ball during a single bounce. (a) The horizontal velocity is constant. (b) The vertical velocity is changing at a constant rate, implying a constant acceleration.

As in the position graphs (Figure 2.2.2) the horizontal velocity graph (Figure 2.2.3a) and the vertical velocity graph (Figure 2.2.3b) are noticeably different. These differences are highlighted below.

Horizontally:

- The ball is constantly moving away from the origin, shown by the positive velocity value.
- The graph is a straight line with a regular interval between each point.
- The horizontal velocity is constant. With no forces acting on the ball horizontally; the ball remains at constant velocity due to inertia.

Vertically:

- The speed of the ball was greatest at the start of the bounce and at the end of the bounce. The velocity of the ball was zero at the top of the bounce, indicating a turning point in its motion.
- The graph is a straight line with a regular interval between each point.
- The constant negative gradient of the graph indicates the ball is experiencing a constant downward acceleration, and therefore, constant force.

As the only force present on the ball is vertical, this will not affect the horizontal motion. Another way of saying this is that the vertical and horizontal components of motion (velocity, displacement and acceleration) are independent of each other. A change in one of these values in one direction will not affect the value in the other direction.

Time is the exception. Time is not a vector quantity, so the time taken for the ball to travel horizontally will be the same as the time taken to travel vertically. A ball cannot be in flight for 5 seconds horizontally and 8 seconds vertically, it has either landed or not. Time behaving identically in both directions often acts as a key part of solving projectile motion problems, covered later in the chapter.

A clear example of the independence of horizontal and vertical motion is shown in Figure 2.2.4. If a ball is launched horizontally at the same time as another is dropped, both objects will hit the ground simultaneously.

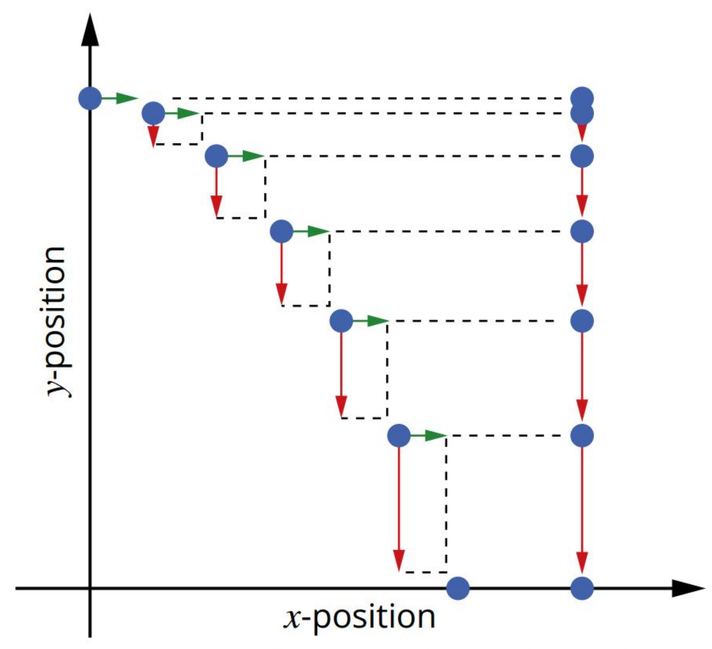


FIGURE 2.2.4 A ball launched horizontally and a dropped ball both hit the ground simultaneously. The motion in each direction is independent. Vertically, both objects behave the same way under gravity.

Applying equations of motion to the flight of a ball

In *Pearson Physics Queensland Units 1 & 2*, the equations of motion were explained and applied to straight-line motion in one dimension. These same equations can be applied to the more complex two-dimensional motion of an object in flight. This is because two-dimensional motion, such as that of the bouncing ball, can be broken into independent vertical and horizontal components using the techniques described so far in this chapter.

PROJECTILES

A **projectile** is any object that is thrown or 'projected' into the air and is moving freely, that is, it has no power source (such as a rocket engine or propeller) driving it. A netball as it is passed, a cricket ball that is hit for six, and an aerial skier flying through the air are all examples of projectiles. This section considers projectiles that are launched horizontally and uses the laws of motion to solve problems involving this type of motion.

Projectile motion

It is a common misconception that when a projectile travels forwards through the air, it has a forward acting force on it. This is incorrect. There was a forward acting force as the projectile was launched, but once the projectile is released, this force is no longer acting.

FIGURE 2.2.5 The motorcycle and rider are travelling in parabolic paths as they fly through the air.

In fact, if air resistance is ignored, the only force acting on a projectile during its flight is its weight, which is the force due to gravity, F_g. This force is constant and always directed vertically downwards. Given that the only force acting on a projectile is the force due to gravity, F_g, it follows that the projectile must have a vertical acceleration of $9.8\,\mathrm{m\,s^{-2}}$ downwards throughout its motion. This causes the projectile to continually deviate from a straight-line path to follow a symmetrical parabolic path (Figure 2.2.5). This motion is known as **freefall**.

Projectile motion is quite complex compared to straight-line motion. It must be analysed by considering the horizontal and vertical components independently.

> In the vertical direction, a projectile accelerates downwards due to the force of gravity at a rate of $9.8\,\mathrm{m\,s^{-2}}$.
>
> In the horizontal direction a projectile has a uniform velocity, as there are no forces acting in this direction (if air resistance is ignored). So, the horizontal acceleration is zero.

Projectiles launched horizontally

Projectiles can be launched at any angle. To analyse most scenarios, the launch velocity needs to be resolved into vertical and horizontal components using trigonometry. For projectiles launched horizontally, calculating the vector components of the launch velocity is straightforward. That's because the initial vertical velocity is zero (but increases downwardly during the flight). The horizontal velocity is constant and is equal to the launch velocity.

Solving problems with projectiles launched horizontally

- Construct a diagram showing the projectile's motion to set the problem out clearly. Write out the information supplied for the horizontal and vertical components separately.
- In the horizontal direction the velocity of the projectile is constant, so the only formula needed is $u_x = v_x = \frac{s_x}{t}$.
- In the vertical direction, the projectile is moving with a constant acceleration ($9.8\,\mathrm{m\,s^{-2}}$ down), and so the equations of motion for uniform acceleration must be used. These include:

$$v_y = u_y + gt$$
$$s_y = u_y t + \frac{1}{2}gt^2$$
$$v_y^{\,2} = u_y^{\,2} + 2gs_y$$

- In the vertical direction it is important to clearly specify whether up or down is the positive or negative direction. Either choice will work just as effectively, but the same convention needs to be used consistently throughout each problem.
- Pythagoras' theorem can be used to determine the speed of the projectile at any point.
- If the velocity of the projectile is required, provide a direction with respect to the horizontal plane as well as the speed of the projectile.

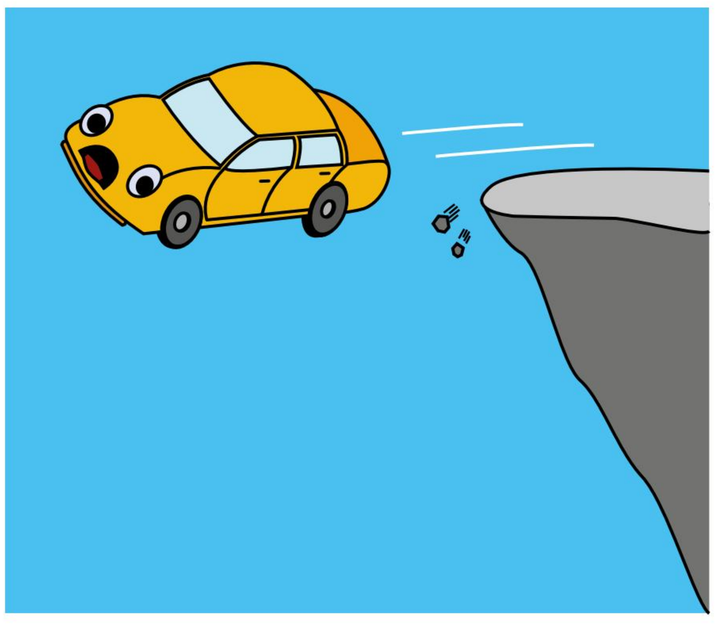


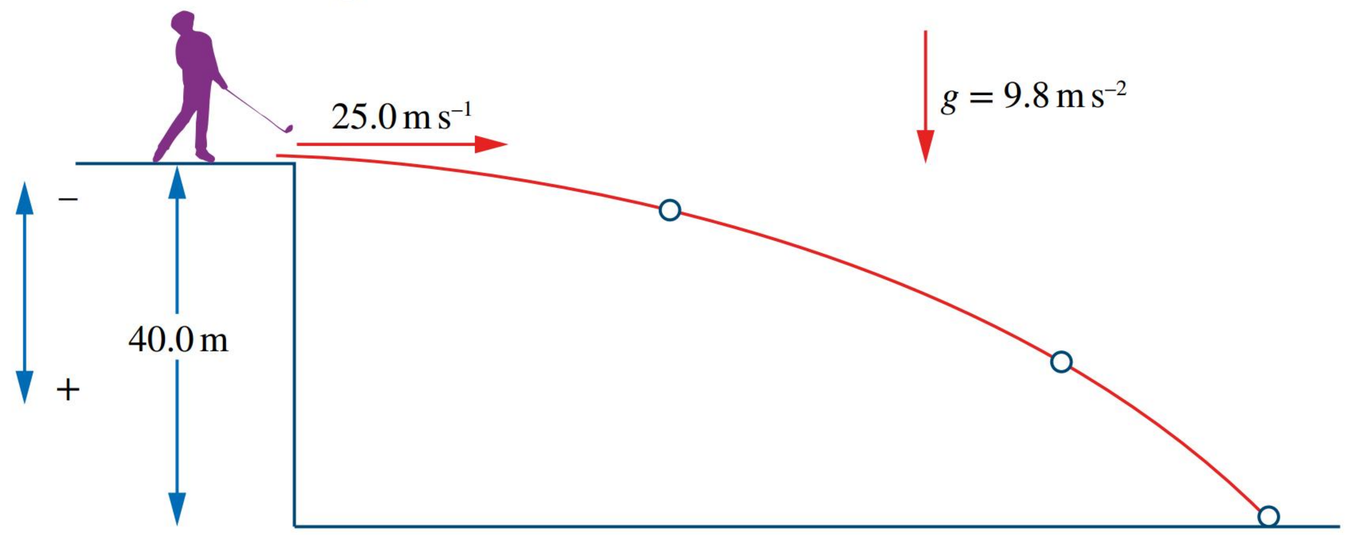
FIGURE 2.2.6 In real life, this car would start falling as soon as it leaves the clifftop, and it would travel in a parabolic arc.

> It is easy to get the wrong idea about projectile motion when you watch cartoon characters running or driving off cliffs. In many cartoons, the character leaves the cliff and travels horizontally outwards, stopping in mid-air (Figure 2.2.6). Once they realise where they are, they immediately fall vertically downwards. This is not what happens in reality: the character would start falling in a smooth parabolic arc as soon as they leave the clifftop.

Worked example 2.2.1

PROJECTILE LAUNCHED HORIZONTALLY

A golf ball of mass 150 g is hit horizontally from the top of a 40.0 m high cliff with a speed of 25.0 m s^{-1}. Using $g = 9.8\,\text{m s}^{-2}$ and ignoring air resistance, calculate the following values.

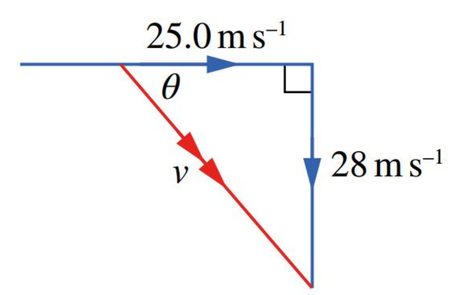


a Calculate the time that the ball takes to land.

Thinking	Working
Mass does not affect the projectile's motion.	The 150 g mass value can be ignored.
Let the downwards direction be positive. Write down the information relevant to the vertical component of the motion. Note that the instant the ball is hit, it is travelling only horizontally, so its initial vertical velocity is zero.	Down is positive. Vertically: $u_y = 0\,\text{m s}^{-1}$ $s_y = 40.0\,\text{m}$ $g = 9.8\,\text{m s}^{-2}$ $t = ?$
In the vertical direction, the ball has constant acceleration, so use equations for uniform acceleration. Select the equation that best fits the information you have.	$s_y = u_y t + \frac{1}{2}gt^2$
Substitute values, rearrange and solve for t.	$40.0 = 0 + \frac{1}{2} \times 9.8 \times t^2$ $t = \sqrt{\frac{40.0}{4.90}}$ $= 2.857 \approx 2.9\,\text{s}$

b Calculate the distance that the ball travels from the base of the cliff (that is, the range of the ball).

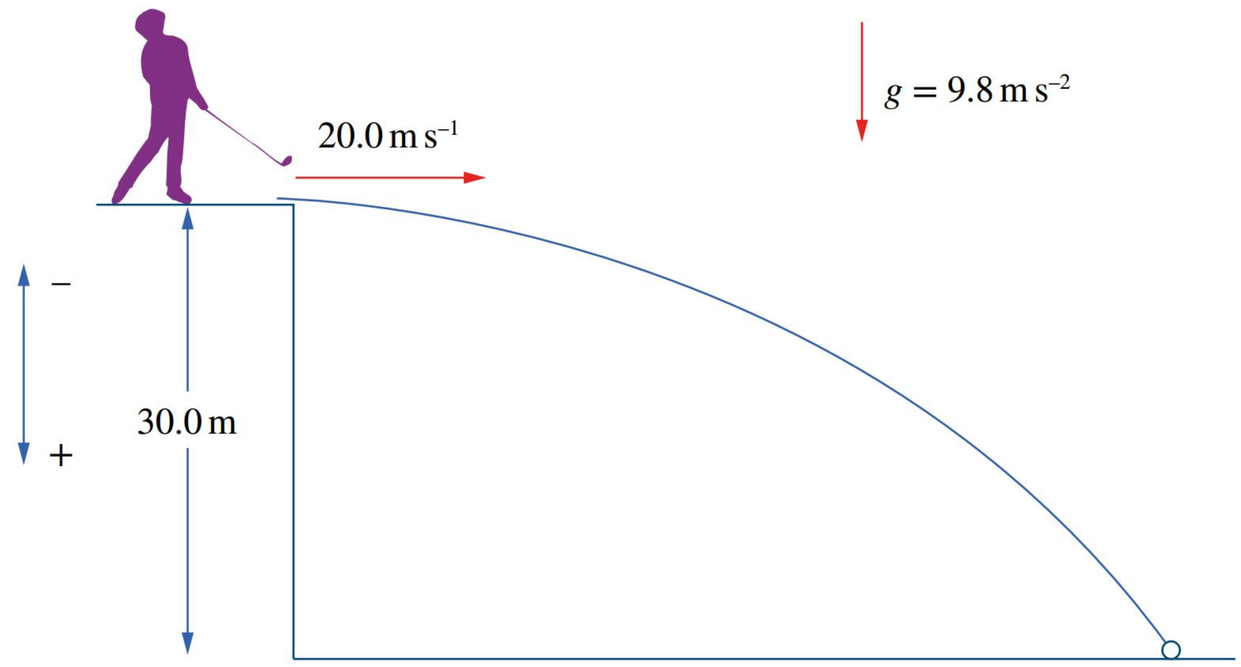
Thinking	Working
Write down the information relevant to the horizontal component of the motion. As the ball is hit horizontally, the initial speed gives the horizontal component of the velocity throughout the flight.	Horizontally: $u_x = 25.0\,\text{m s}^{-1}$ $t = 2.857\,\text{s}$ from part (a) $s_x = ?$

Select the equation that best fits the information you have.	$s_x = u_x t$
Substitute values, rearrange and solve for s_x. Never round off a value until the final calculation, otherwise you will introduce a rounding error.	$s_x = 25.0 \times 2.857$ $= 71\,\text{m}$ Note that the mass of the ball does not affect its motion. This is true for all objects in projectile motion or in freefall.
c Calculate the velocity of the ball as it lands.	
Thinking	**Working**
Find the horizontal and vertical components of the ball's speed as it lands. Write down the information relevant to both the vertical and horizontal components.	Horizontally: $u_x = v_x = 25.0\,\text{m s}^{-1}$ Vertically, with down as positive: $u_y = 0$ $g = 9.8\,\text{m s}^{-2}$ $s_y = 40.0\,\text{m}$ $t = 2.857\,\text{s}$ $v_y = ?$
To find the final vertical speed, use the equation for uniform acceleration that best fits the information you have.	$v_y = u_y + gt$
Substitute values, rearrange and solve for the variable you are looking for, in this case v_y.	Vertically: $v_y = 0 + 9.8 \times 2.857$ $= 28\,\text{m s}^{-1}$ down
Add the components as vectors.	
Use Pythagoras' theorem to work out the actual speed, v, of the ball.	$v = \sqrt{v_x^2 + v_y^2}$ $= \sqrt{25.0^2 + 28^2}$ $= \sqrt{1409}$ $= 38\,\text{m s}^{-1}$
Use trigonometry to find the angle, θ.	$\theta = \tan^{-1}\left(\frac{28}{25.0}\right)$ $= 48°$
Indicate the velocity with a magnitude and direction relative to the horizontal.	The final velocity of the ball is $38\,\text{m s}^{-1}$ at 48° below the horizontal.

➤ Try yourself 2.2.1

PROJECTILE LAUNCHED HORIZONTALLY

A golf ball of mass 100.0 g is hit horizontally from the top of a 30.0 m high cliff with a speed of 20.0 m s^{-1}. Using $g = 9.8\,\text{m s}^{-2}$ and ignoring air resistance, calculate the following values.



a Calculate the time that the ball takes to land.

b Calculate the distance that the ball travels from the base of the cliff (that is, the range of the ball).

c Calculate the velocity of the ball as it lands.

Projectiles launched at an angle

The previous section looked at horizontally launched projectiles. More commonly, projectiles are launched at an angle to the horizontal direction, by being thrown forwards and upwards at the same time, for example, shooting for a goal in basketball (Figure 2.2.7). Once the ball is released, the only force acting on the ball (in the absence of air resistance) is gravity, pulling the ball down to Earth.

In this section, the principles covering horizontal projectile motion will still apply, as described by the first law of motion.

As with projectiles launched horizontally, if **drag** forces are ignored, the only force acting on a projectile launched at an angle to the horizontal is gravity, F_g.

Gravity acts vertically downwards and so it has no effect on the horizontal motion of the projectile. Recall that the vertical and horizontal components of the motion are independent of each other and once again must be treated separately.

In the vertical direction, a projectile accelerates due to the force of gravity, that is, at a rate of 9.8 m s^{-2} downwards. The effect of the force due to gravity is that the vertical component of the projectile's velocity decreases as the projectile rises. Momentarily, the velocity will be zero at the very top of the flight and then its magnitude increases downwardly as the projectile descends.

In the horizontal direction a projectile has a uniform velocity, since there are no forces acting in this direction (if air resistance is ignored).

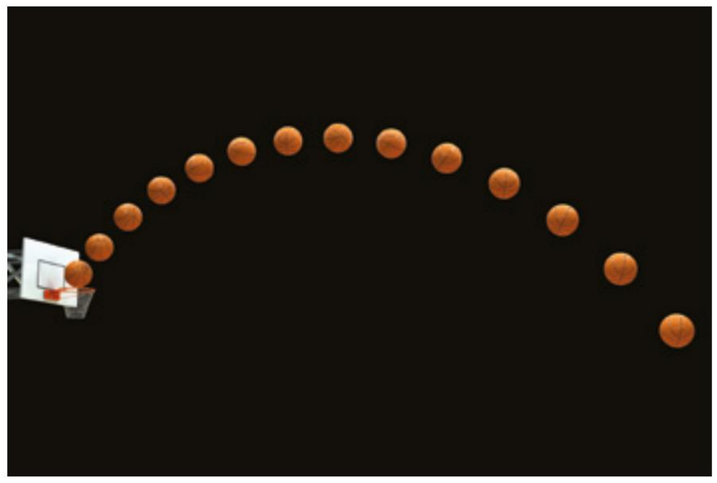


FIGURE 2.2.7 The basketball was thrown up towards the basket, travelling in a smooth parabolic path.

Projectile trajectories

The path taken by a projectile is symmetrical and parabolic. It is the independent behaviour of the horizontal and vertical components of projectile motion that causes these parabolic trajectories. This symmetrical behaviour can be discovered by investigating the horizontal range of a projectile as it is launched at various angles (Table 2.2.1).

From Table 2.2.1 a clear pattern exists in the horizontal component of the projectile, and can be visualised through plotting the data (Figure 2.2.8).

TABLE 2.2.1 The distance travelled by a projectile at $4\,m\,s^{-1}$ at various angles.

Angle of elevation (degrees,°)	Horizontal displacement (m)
15.0	0.82
30.0	1.41
45.0	1.63
60.0	1.41
75.0	0.82

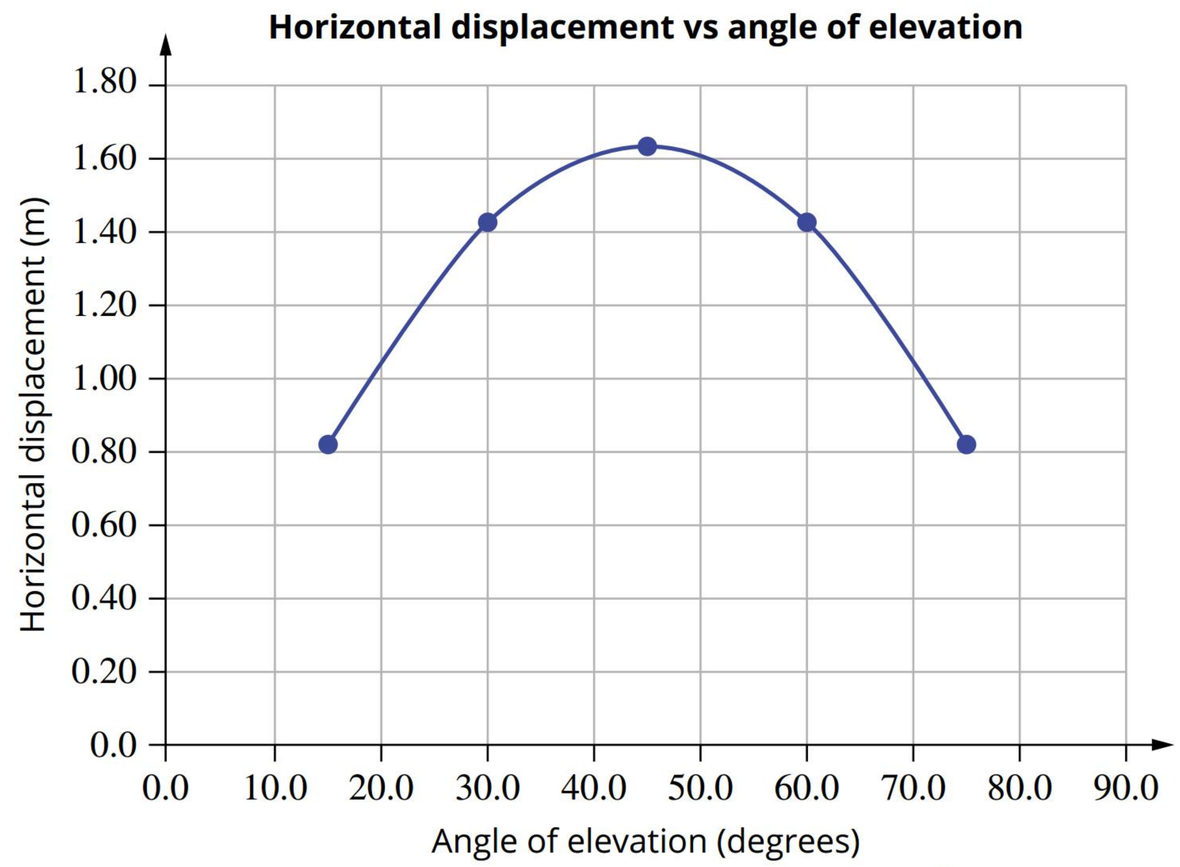


FIGURE 2.2.8 A graph shows the distance travelled by a projectile at $4\,m\,s^{-1}$ at various angles.

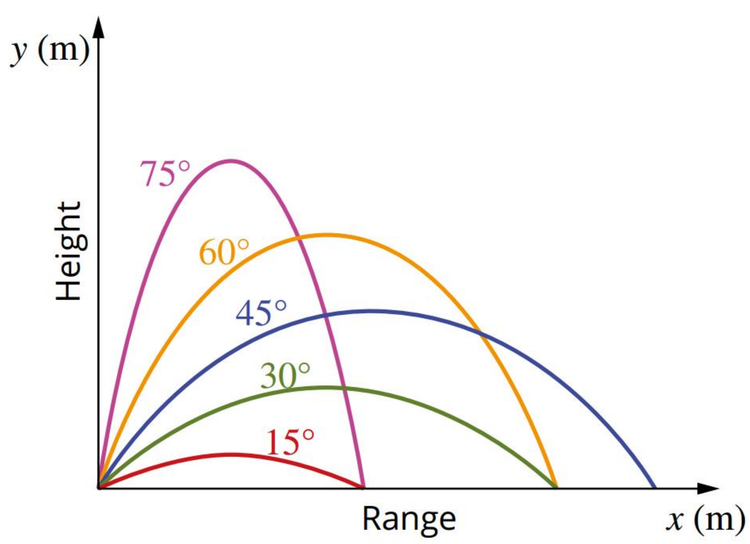


FIGURE 2.2.9 A depiction of the trajectories travelled by a projectile launched at various angles.

Figure 2.2.9 demonstrates the trajectory of a projectile at various angles. It can be seen here how complementary angles achieve the same range. At an angle of 15°, the projectile travels low to the ground with a high horizontal velocity, but a smaller time of flight. At an angle of 75° the projectile travels more vertically with a significantly reduced horizontal velocity, but the time of flight is extended considerably. These two variables counterbalance each other to achieve the same result.

Solving problems with projectiles launched at an angle

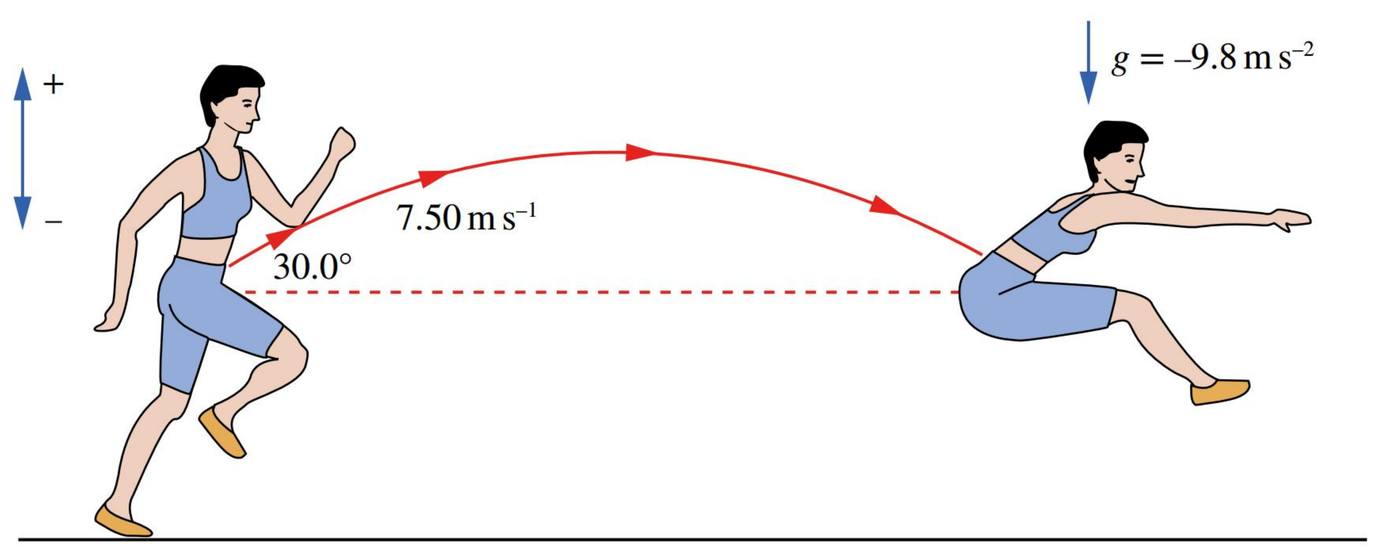
General rules for solving problems involving projectile motion were given in the previous section; see page 19 for a reminder.

If a projectile is launched at an angle to the horizontal, the initial vertical velocity will not be zero, and trigonometry can be used to find both the initial horizontal and vertical components of the velocity. Pythagoras' theorem can be used to determine the actual velocity of the projectile at any point, as well as a direction with respect to the horizontal plane.

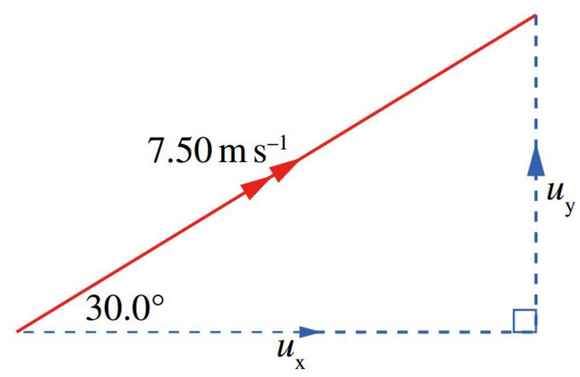
Worked example 2.2.2

LAUNCH AT AN ANGLE

A 65.0 kg athlete in a long-jump event leaps with a velocity of $7.50\,m\,s^{-1}$ at an angle of 30.0° to the horizontal.



For the following questions, treat the athlete as a point mass, ignore air resistance and use $g = -9.8\,m\,s^{-2}$.

a Calculate the athlete's velocity at the highest point.	
Thinking	**Working**
Mass does not affect the projectile's motion.	The 65.0 kg mass value can be ignored.
Find the magnitudes of the horizontal and vertical components of the initial velocity.	 Using trigonometry: $u_x = 7.50 \cos 30.0°$ $= 6.50\,\text{m s}^{-1}$ $u_y = 7.50 \sin 30.0°$ $= 3.75\,\text{m s}^{-1}$
At the highest point of the athlete's jump the vertical component of the velocity is zero, therefore the resultant velocity at this point is just the horizontal velocity.	At maximum height: $v_x = 6.50\,\text{m s}^{-1}$ horizontally to the right.

b Calculate the maximum height gained by the athlete during the jump.	
Thinking	**Working**
To find the maximum height that is gained, you must work with the vertical component of the velocity. Recall that the vertical component of velocity at the highest point is zero. As gravity acts in the opposite direction from the jump, the initial vertical velocity is made positive, and acceleration from gravity is made negative.	Vertically, taking up as positive: $u_y = 3.75\,\text{m s}^{-1}$ $g = -9.8\,\text{m s}^{-2}$ $v_y = 0$ $s_y = ?$
Substitute these values into an appropriate equation for uniform acceleration.	$v_y^2 = u_y^2 + 2gs_y$ $0 = 3.75^2 + 2 \times -9.8 \times s_y$
Rearrange and solve for s_y.	$s_y = \dfrac{3.75^2}{19.6}$ $= 0.717\,\text{m}$

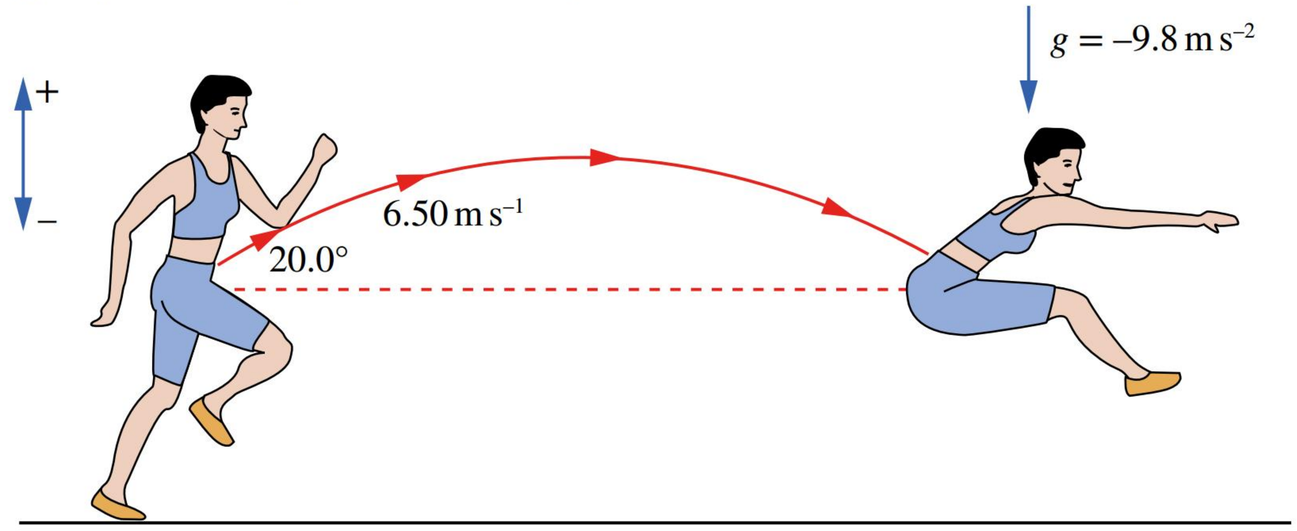
c Calculate the total time the athlete is in the air, assuming a return to the original height.	
Thinking	**Working**
The take-off height and landing height are the same.	The initial velocities in the *x* and *y* direction are the same as the final velocities in the *x* and *y* direction (with a negative value for the final *y* velocity).
As the motion is symmetrical, the time taken to complete the motion will be double that taken to reach the maximum height. First, the time it takes to reach the highest point must be found.	Vertically, taking up as positive: $u_y = 3.75\,\text{m s}^{-1}$ $g = -9.8\,\text{m s}^{-2}$ $v_y = 0$ $t = ?$

Insert these values into an appropriate equation for uniform acceleration.	$v_y = u_y + gt$ $0 = 3.75 - 9.8t$
Rearrange the formula and solve for t.	$t = \frac{3.75}{9.8}$ $= 0.383\,\text{s}$
The time to complete the motion is double the time it takes to reach the maximum height.	Total time $= 2 \times 0.383$ $= 0.765\,\text{s}$

➤ Try yourself 2.2.2

LAUNCH AT AN ANGLE

A 50.0 kg athlete in a long-jump event leaps with a velocity of $6.50\,\text{m}\,\text{s}^{-1}$ at 20.0° to the horizontal.



For the following questions, treat the athlete as a point mass, ignore air resistance and use $g = -9.8\,\text{m}\,\text{s}^{-2}$.

a Calculate the athlete's velocity at the highest point.

b Calculate the maximum height gained by the athlete's centre of mass during the jump.

c Calculate the total time the athlete is in the air, assuming a return to the original height.

2.2 Review

SUMMARY

- If air resistance is ignored, the only force acting on a projectile is its weight (the force of gravity, F_g). This results in the projectile having a vertical acceleration of $9.8\,\text{m}\,\text{s}^{-2}$ down during its flight.
- Projectiles move in parabolic paths that can be analysed by considering the horizontal and vertical components of the motion.
- If a projectile is launched at an upward angle from a horizontal surface the flight will be symmetrical around the point of maximum height.
- The horizontal component and vertical components of motion are independent of each other; they do not affect each other.
- The following equations of motion for uniform acceleration must be used for the vertical component of the motion:

$$v_y = u_y + gt$$
$$s_y = u_y t + \frac{1}{2}gt^2$$
$$v_y^2 = u_y^2 + 2gs_y$$

- The horizontal velocity of a projectile remains constant throughout its flight if air resistance is ignored. Therefore, the following equation for average velocity can be used for this component of the motion:

$$u_x = v_x = \frac{s_x}{t}$$

- The vertical velocity of a projectile is zero at its highest point of motion.

2.2 Review

KEY QUESTIONS

For the following questions, assume that the acceleration due to gravity is $9.8\,m\,s^{-2}$ and ignore the effects of air resistance.

Describe

1 Describe the horizontal velocity of a projectile throughout its flight.

2 State the position in the flight of a projectile when its vertical velocity is equal to zero.

3 Identify the force which acts on a projectile throughout its flight.

Apply

4 Describe the shape of the path of a projectile if the horizontal and vertical components of its velocity are equal.

5 Calculate the horizontal velocity of a projectile launched at $12.0\,m\,s^{-1}$ at an angle of 32.0 degrees.

6 Calculate the magnitude of the velocity of a projectile if it has a horizontal speed of $0.8\,m\,s^{-1}$ and a vertical speed of $-1.6\,m\,s^{-1}$

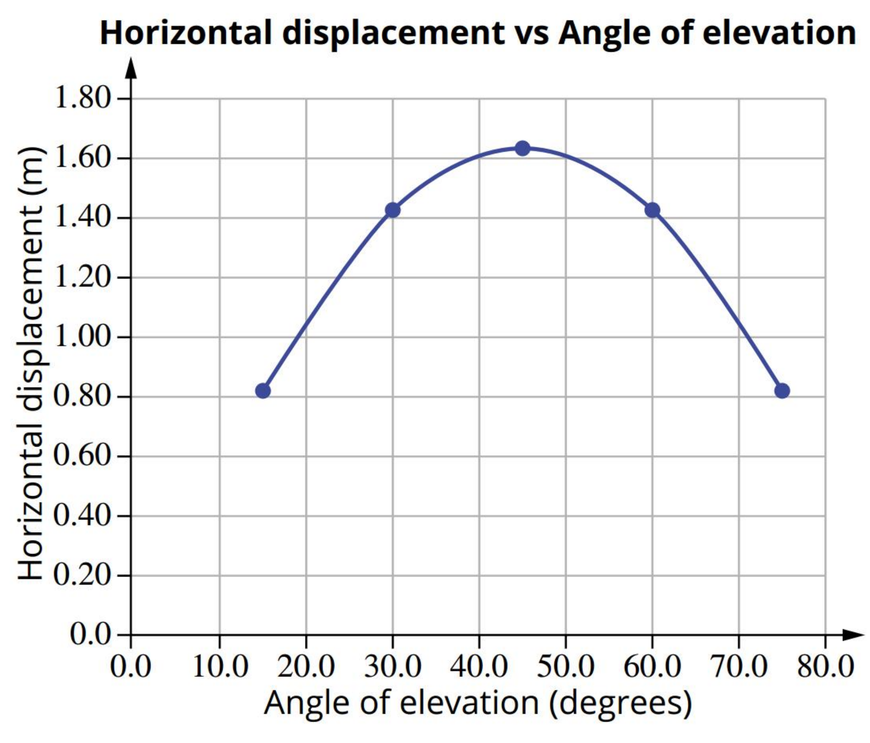
Analyse

7 The horizontal range of a projectile launched at various angles of elevation is shown in the data table below.

Angle of elevation (degrees)	Horizontal displacement (m)
10.0	0.17
20.0	0.32
30.0	0.43
40.0	0.49

Use the data to predict the horizontal displacement of a projectile launched at 60 degrees.

8 The graph below shows the horizontal displacement of a projectile launched at various angles of elevation.

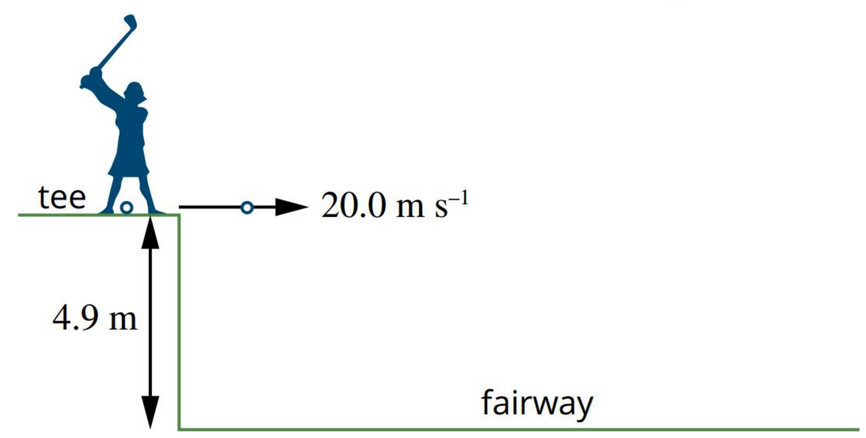


Use the graph to infer the suitable launch angles which would produce a range of approximately 1.4 m

9 A marble travelling at $2.0\,m\,s^{-1}$ rolls off a jump, angled at 30° above the horizontal, and takes 0.75 s to reach the floor.

- **a** Calculate how far the marble travels horizontally before landing.
- **b** Calculate the vertical component of the speed of the marble as it lands.
- **c** Calculate the speed of the marble as it lands.

10 A golfer practising on a range with an elevated tee 4.9 m above the fairway is able to strike a ball so that it leaves the club with a horizontal velocity of $20.0\,m\,s^{-1}$.



- **a** Calculate the time taken for the ball to land on the fairway after being hit.
- **b** Calculate the horizontal distance the ball travels before landing on the fairway.
- **c** Calculate the acceleration of the ball 0.50 s after being hit.
- **d** Calculate the speed of the ball 0.80 s after it leaves the club.
- **e** Calculate the speed with which the ball hits the ground.

11 A tourist stands on top of a sea cliff that is 80.0 m high. The tourist throws a rock horizontally at $25.0\,m\,s^{-1}$ into the sea.

- **a** Determine the speed of the rock as it reaches the water.
- **b** Identify the angle at which the rock is travelling relative to the horizontal as it reaches the water.

12 A skateboard travelling at $4.0\,m\,s^{-1}$ rolls off a surface that is angled downward at 15° and that is 1.2 m high.

- **a** Determine how long the board takes to hit the ground.
- **b** Determine how far the board lands from the base of the bench.
- **c** Calculate the magnitude and direction of the acceleration of the board just before it lands.

Chapter review

02

KEY TERMS

acceleration
angle
component
displacement
drag
freefall
parallel
perpendicular
projectile
Pythagoras' theorem
resolve
resolution
trigonometric ratios
vector
velocity

KEY QUESTIONS

For the following questions, assume that the acceleration due to gravity is $9.8\,m\,s^{-2}$ and ignore the effects of air resistance.

Describe

1 Identify which of the following options best describes the projectile motion of a stone that is thrown horizontally at $5\,m\,s^{-1}$ as it falls towards a pond.

A Its speed decreases.
B It travels in a circular path.
C There is a driving force acting on it.
D The only force acting on it is gravity.

2 Identify which of the following options that best describes a javelin at the highest point of its path, after being launched at 40° above the horizontal.

A It has zero acceleration.
B It is at its minimum speed.
C There are no forces acting on it since it is in freefall.
D There are forwards and downwards forces acting on it.

3 Identify which of the following statements that best describes the path of golf balls hit on the Moon by American astronaut Alan Shepard in 1971.

A The balls went into orbit.
B The balls travelled in parabolic arcs.
C The balls travelled in straight lines because there is no gravity.
D The balls travelled a shorter distance than if they had been hit in an identical manner on Earth.

4 When a soccer ball is kicked, it is launched at ground level, and lands at ground level.
Identify the option below which best describes the relationship between the upward travel time and the downward travel time of the ball.

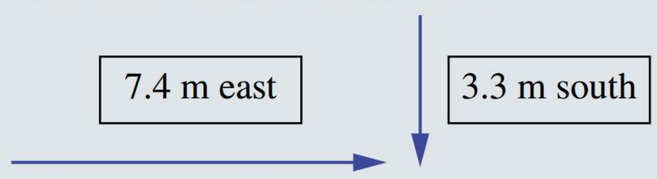
A The upward travel time is greater than the downward travel time.
B The upward travel time is less than the downward travel time.
C The upward travel time is equal to the downward travel time.
D The upward travel time is inversely proportional to the downward travel time.

5 Describe the horizontal velocity of a basketball as it is thrown towards the hoop in a shot for goal.

6 State where the vertical velocity of a ball in flight will be at a minimum.

Apply

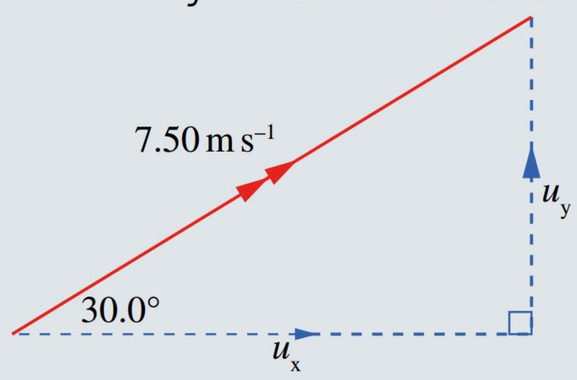
7 Two vectors are shown below.



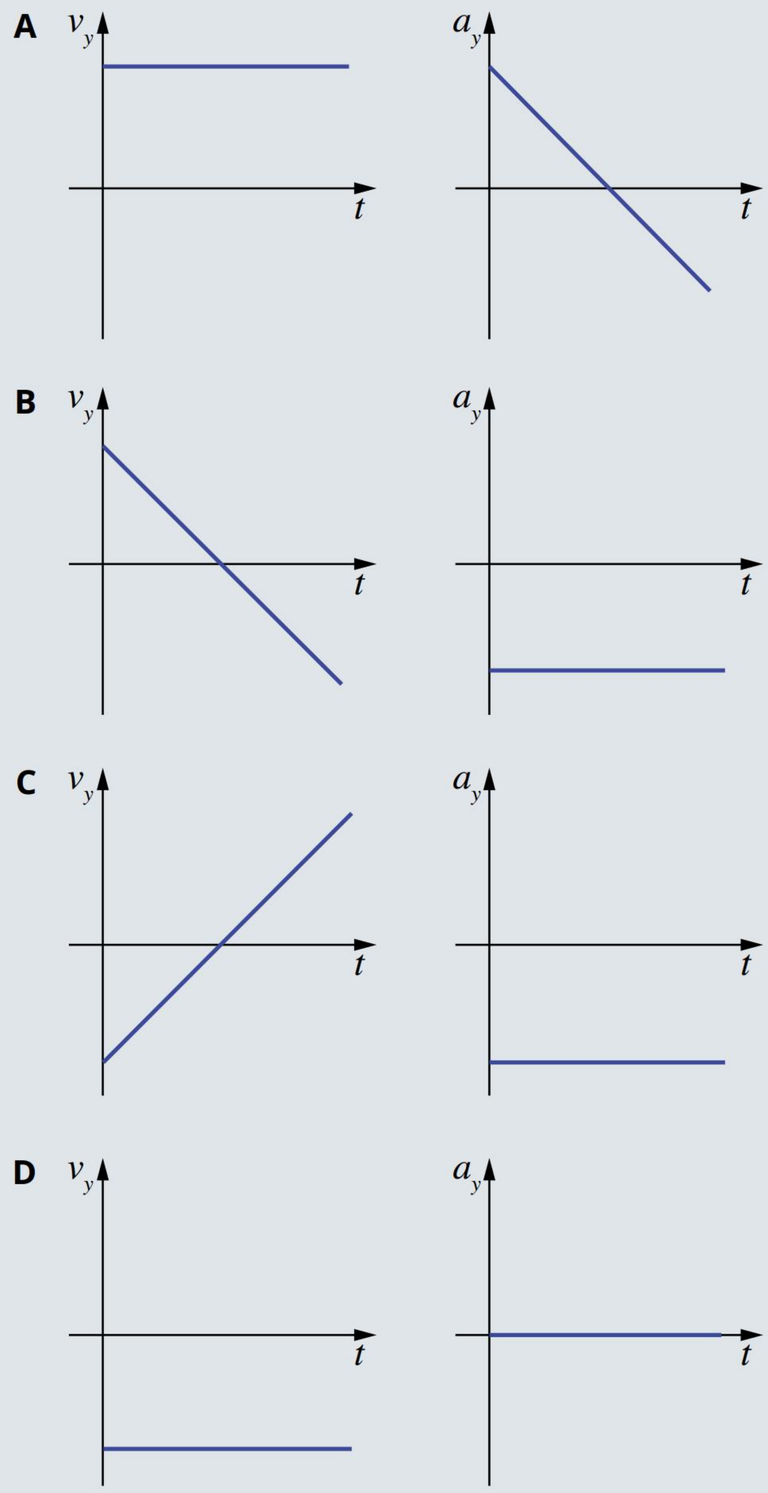
Calculate the magnitude of the resultant vector. The resultant is:

A 3.3 m
B 8.1 m
C 10.7 m
D 65.65 m

8 Calculate the horizontal and vertical components of the velocity vector shown below

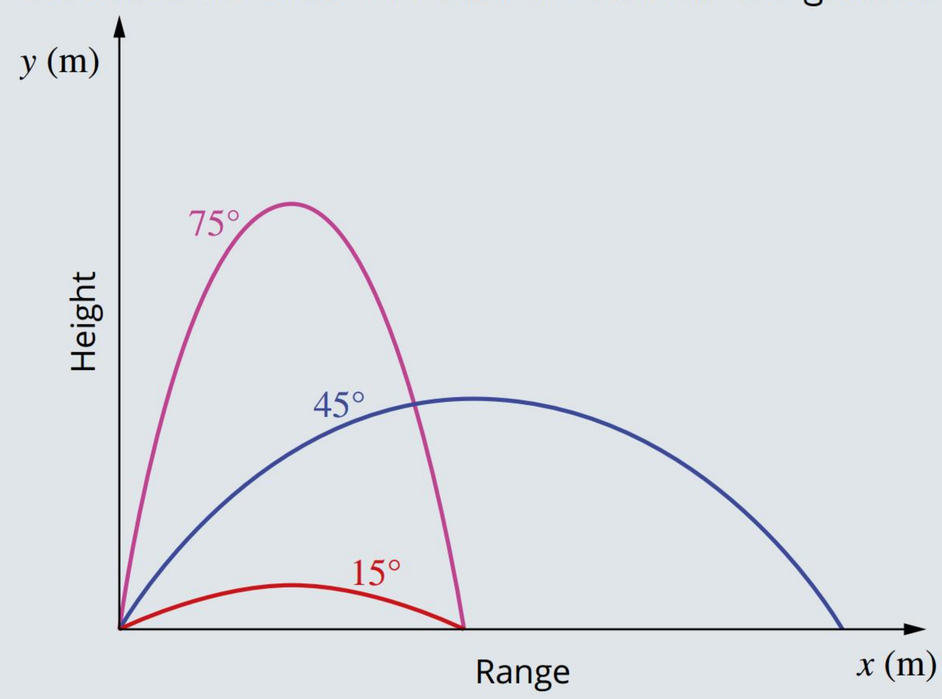


9 A projectile is launched at an angle above the horizontal. Identify which of the following pair of graphs accurately depicts the vertical component of velocity and acceleration of the object



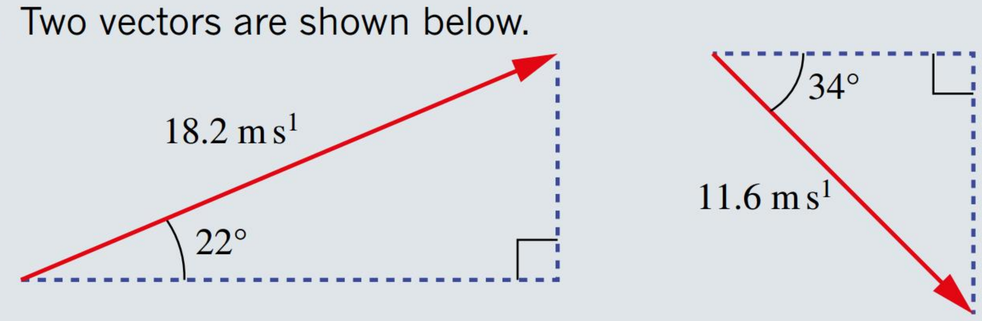
10 Three projectiles of equal mass and velocity are launched at different angles. Their trajectories are shown in the figure below.

Identify the following option which accurately describes the order in which the balls hit the ground.



A The 15 degree projectile lands first.
B The 45 degree projectile lands first.
C The 75 degree projectile lands first.
D All three projectiles land simultaneously.

11 Two vectors are shown below.



Identify which of the following options that correctly describes the resultant vector.

A 26.5 m s^{-1} at 0.7 degrees above the horizontal
B 15.2 m s^{-1} at 61.4 degrees above the horizontal
C 29.6 m s^{-1} at 26.7 degrees above the horizontal
D 7.3 m s^{-1} at 2.6 degrees above the horizontal

Analyse

The following information relates to questions **12–14.**

A group of students have conducted a projectile motion experiment. The results for their experiment are in the table below.

	Horizontal displacement (m)			
Angle of elevation (degrees)	**Trial 1**	**Trial 2**	**Trial 3**	**Average**
5	0.47	0.47	0.49	0.47
10	0.97	0.97	1.02	0.98
15	1.38	1.38	1.35	1.37
20	1.95	1.73	1.75	1.81
25	2.14	2.08	2.16	
30	2.46	2.46	2.52	2.48

12 Calculate the average for the 25 degree trial.

13 Identify any outliers in the data, providing a reason for your choice.

14 Identify at least one limitation based on the results of the experiment.

The following information relates to Questions **15–17**.

A rugby player place-kicks a ball from the kicking tee with an initial velocity such that the vertical component is $5.0\,m\,s^{-1}$ and the horizontal component is $10.0\,m\,s^{-1}$. Assume the launch and landing heights are the same.

15 Determine the vertical and horizontal components of the ball's velocity at the point just before landing.

16 Calculate the value of the vertical component of the velocity 0.35 s after leaving the kicking tee.

17 **a** Calculate how long the ball will be in the air before landing.

b Calculate the horizontal distance the ball travels.

18 Charlie swims across a river that is flowing at a velocity of $1.3\,m\,s^{-1}$ south. He swims so that his direction of travel is due east, and his average velocity in swimming across the river is $0.43\,m\,s^{-1}$. Calculate the vector sum of Charlie's velocity and that of the river.

19 Calculate the resultant force if a 20.0 N upwards force is subtracted from a 32 N force acting to the right.

20 A projectile is launched such that the vertical component of velocity is $27\,m\,s^{-1}$. Calculate the minimum velocity required to achieve a horizontal range of 220 m. Assume the launch height and landing height are equal.

21 Calculate the total horizontal distance a ball travels when an AFL football player kicks towards the goal from the 50 metre line. The ball leaves his foot at an angle of 45° from the horizontal and with a speed of $23.0\,m\,s^{-1}$.

22 Two identical tennis balls X and Y are hit horizontally from a point 2.0 m above the ground with different initial speeds: ball X has an initial speed of $5.0\,m\,s^{-1}$, and ball Y has an initial speed of $10.0\,m\,s^{-1}$.

Contrast the horizontal displacement of each ball before they bounce.

23 An archer stands on top of a platform that is 20.0 m high and fires an arrow horizontally at $50.0\,m\,s^{-1}$. Calculate the velocity of the arrow as it reaches the ground.

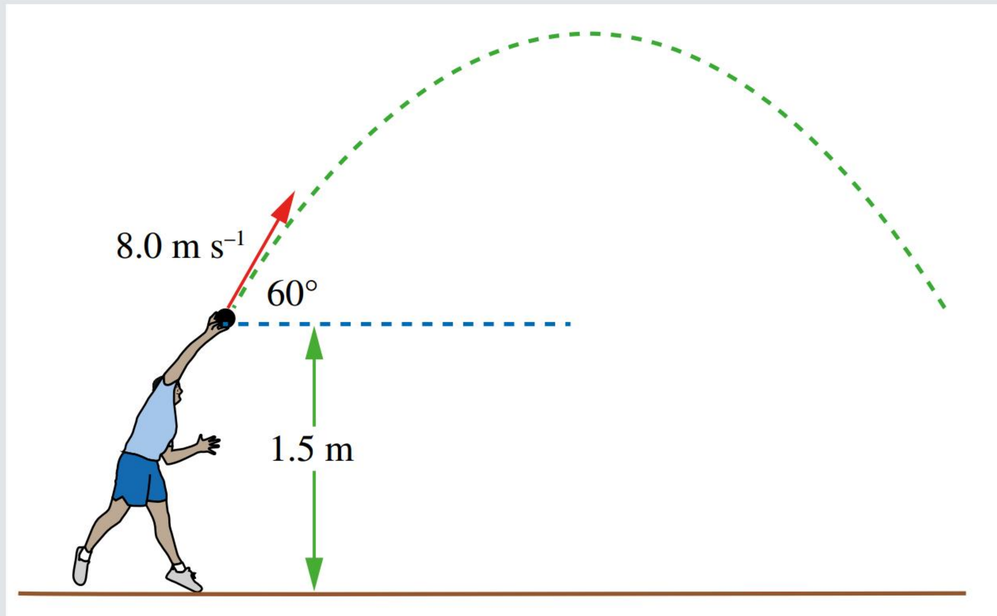
24 A bowling ball of mass 7.5 kg travelling at $10.0\,m\,s^{-1}$ rolls off a horizontal table 1.00 m high.

a Calculate the velocity of the ball as it reaches the floor.

b Calculate the horizontal distance travelled by the ball as it falls.

c Draw a diagram showing the forces acting on the ball as it falls towards the floor.

25 In a shot-put event a 2.0 kg shot is launched from a height of 1.5 m, with an initial velocity of $8.0\,m\,s^{-1}$ at an angle of 60° to the horizontal.



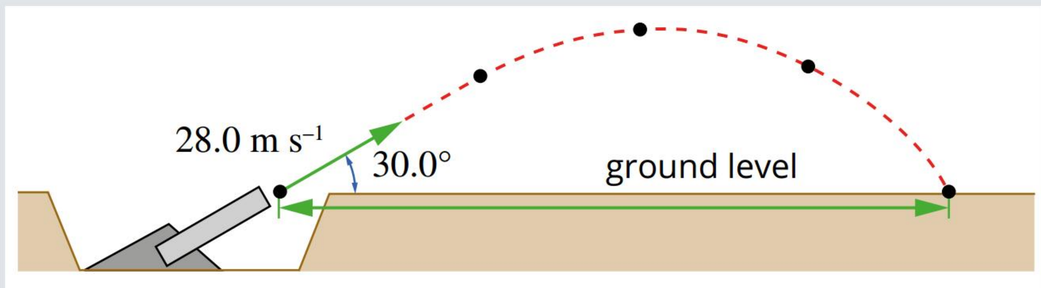
a Calculate the initial horizontal and vertical velocities of the shot.

b Calculate the maximum height from the ground that is reached by the shot.

c Calculate the speed of the shot when it reaches its maximum height.

The following information relates to Questions **26–30**.

A senior physics class conducting a research project on projectile motion constructs a device that can launch a cricket ball. The launching device is designed so that the ball can be launched at ground level with an initial velocity of $28.0\,m\,s^{-1}$ at an angle of 30.0° to the horizontal.



26 Calculate the horizontal and vertical components of the velocity of the ball:

a initially

b after 1.0 s

c after 2.0 s.

27 Determine the velocity of the cricket ball after 2.0 s.

28 Determine the speed of the ball as it lands.

29 Calculate the horizontal distance the ball travels before landing, that is, its range.

30 Calculate the net force acting on the post in the following situation: A force of 2650 N is acting due east on the post due to a rope from a tractor attempting to pull the post out of the ground, while a force of 880 N is acting at an angle of N62°E on the same post due to a car pulling on a rope attached to the post.

Interpret

31 Predict the angle to the horizontal that will result in a water stream travelling at the greatest distance through the air from a garden hose. The hose is held at ground level, with water travelling at $15\,m\,s^{-1}$.

32 Suppose a projectile launcher is placed at the edge of the table so that the projectile it fires falls to the floor. Calculate the horizontal range on the floor if the projectile is fired at $1.9\,m\,s^{-1}$, assuming the ball is launched 0.85 m above the ground and the launcher is set to 65° upwards from the horizontal.

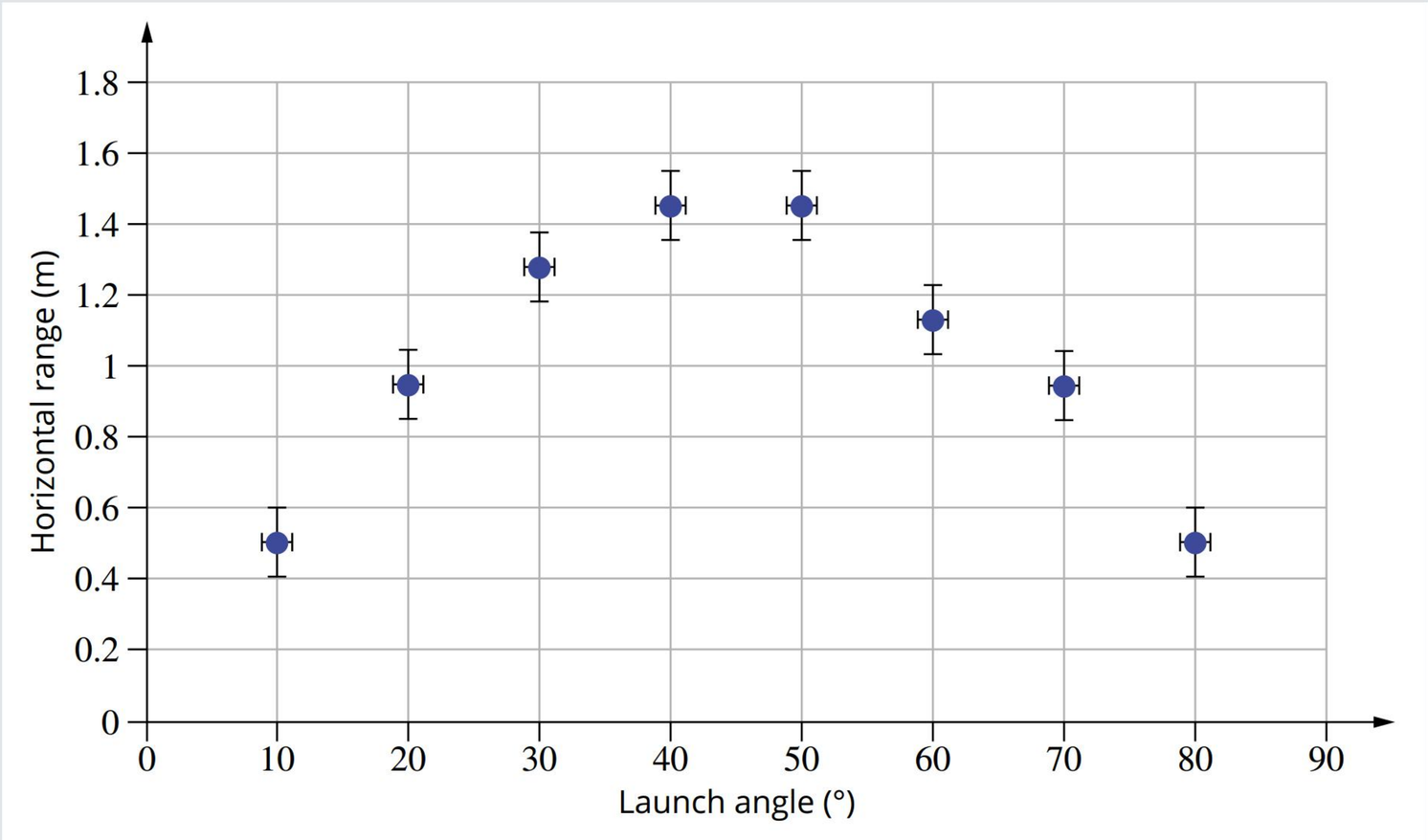
33 An Olympic display needs to be designed where glowing orbs are launched from a boat over a bridge. Explain how the launch angle can be constrained to prevent collision with the bridge. Use a diagram showing the possible trajectories to support your response.

Data analysis

DATA SET 1

The information below applies to Questions **1–4**.

A projectile launcher which shoots a small ball-bearing at a speed of $3.8\,m\,s^{-1}$ was used to investigate the relationship between launch angle and horizontal range. The processed experimental data is shown in the following graph.



Question 1 (1 mark)

Identify the launch angles which produced a range of 0.5 m.

Question 2 (2 marks)

Calculate the initial vertical component of velocity when the ball was launched with an angle of 30°.

Question 3 (1 mark)

Identify the relationship between launch angle and horizontal range.

Question 4 (2 marks)

Identify the launch angle of the data point which may represent an outlier. Provide a reason for your response.

24
25

CHAPTER

03 Inclined planes and circular motion

This chapter explores the forces on objects resting or moving on a surface that is at an angle to the horizontal, also known as inclined planes, as well as objects experiencing circular motion. These forces will be analysed using free-body diagrams and formulae that were introduced in *Pearson Physics Queensland Units 1 & 2*. Inclined planes are used to change the magnitude or direction of a force. They are experienced in many aspects of everyday life from walking up a hill to building skyscrapers. Circular motion explores the idea that if a force is applied perpendicularly (at right angles) to the motion of an object, then the object will change direction. If this force is *continuously* applied at right angles to the motion of an object, then the object will *continue* to change direction, i.e. it will move in uniform circular motion.

Syllabus subject matter

INCLINED PLANES AND CIRCULAR MOTION

- Solve problems involving force due to gravity (weight) and mass using $F_g = mg$. **3.1**
- Describe the concept of normal force. **3.1**
- Describe the forces acting on an object on an inclined plane (e.g. force due to gravity, normal force, tension, frictional force and applied force) through the use of free-body diagrams. **3.1**
- Determine the net force acting on an object on an inclined plane using vector analysis. **3.1**
- Describe the concept of uniform circular motion. **3.2**
- Describe the concepts of average speed and period. **3.2**
- Solve problems involving objects undergoing uniform circular motion at a constant speed using $v = \frac{2\pi r}{T}$ and $a_c = \frac{v^2}{r}$. **3.2**, **3.3**
- Describe the concepts of centripetal acceleration and centripetal force. **3.3**
- Solve problems involving forces acting on objects in uniform circular motion using $F_c = F_{net} = \frac{mv^2}{r}$. **3.3**

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3.1 Inclined planes

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- identify the forces acting on an object moving or resting on a surface at an angle to the horizontal, including the force due to gravity, friction and normal forces
- draw free-body diagrams to show the forces acting on an object on an inclined plane
- use vectors to analyse the net force acting on an object on an inclined plane.

FORCE DUE TO GRAVITY

In *Pearson Physics Queensland Units 1 & 2*, it was shown that a **force** is a push or a pull that can do one or more of the following to any object with mass:

- A force can change an object's velocity by changing its speed.
- A force can change an object's velocity by changing its direction of motion.
- A force can change the shape of an object.

The **force due to gravity** (also referred to as **weight** or simply **gravitational force**) is the force on an object due to its mass being in the presence of a gravitational field, such as Earth's gravitational field. The mass of an object is the same everywhere in the universe, but its gravitational force will change depending on the strength of the gravitational field the object is exposed to. (You will learn more about this in Chapter 4). Any object with mass that is free to move in a gravitational field will experience an **acceleration due to gravity**, g.

The second law of motion can be used to calculate the gravitational force, F_g, of any mass in any gravitational field with an acceleration due to gravity g:

$$F_g = mg$$

g will vary depending on the location, but for objects on the surface of Earth, g is approximately $9.8\,\mathrm{m\,s^{-2}}$ straight down towards the centre of Earth.

> A force is a measure of the push or pull on an object.
>
> It is measured in newtons (N).
>
> It is a vector and so requires a magnitude and a direction to describe it fully.

> Force due to gravity is the force that acts on an object due to its mass in a gravitational field. It is given by:
>
> $$F_g = mg$$

THE NORMAL FORCE

The **normal force** is a very important force that acts on an object that is in contact with a surface. If we are at rest on a horizontal surface, and no other forces are acting, our gravitational force and the normal force acting on us are the same magnitude. These two forces will not be the same magnitude, however, if other forces act or the directions of the forces change, such as when flying in an aeroplane, or moving in an elevator.

The normal force, F_N, is always perpendicular to the surface in contact with the object (Figure 3.1.1). Remember that, although the gravitational force and the normal force may be equal in magnitude and opposite in direction, they are not an action-reaction pair defined by the third law of motion, as both forces are acting on the box from different sources.

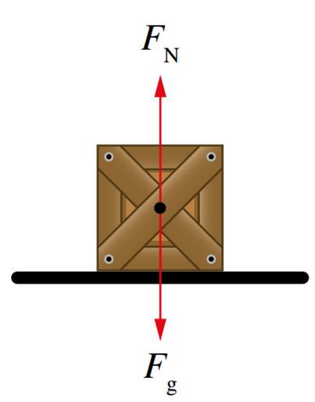


FIGURE 3.1.1 The normal force, F_N, is the force that pushes a mass upwards and is perpendicular to the surface in contact with the object.

In the example shown in Figure 3.1.1, the forces acting on the crate are:

- force due to gravity, F_g, and
- normal force, F_N.

The crate is resting on the ground so the net force must be zero. Using the second law of motion:

$$F_{net} = \text{vector sum of all forces acting on the crate}$$

So,

$$F_{net} = F_N \text{ (as a vector)} + F_g \text{ (as a vector)}$$

> The normal force is a force that acts on an object when the object is in contact with a surface.
>
> The normal force always acts perpendicular to the surface.

The gravitational force and normal force are in a straight line because the surface the crate rests on is exactly horizontal. This means we can set the upwards force as positive and the downwards force as negative. So, the net force becomes:

$$F_{net} = F_N + F_g$$

$$\text{But } F_{net} = 0, \text{ so}$$

$$0 = F_N + F_g$$

$$\therefore F_N = -F_g$$

This shows that the normal force is the same size as the gravitational force but opposite in direction.

FREE-BODY DIAGRAMS

A diagram showing all of the forces acting on a single object is called a **free-body diagram**. Free-body diagrams are used to simplify the process of analysing the forces, and hence the resultant motion of a single object, by only showing forces that act directly on that particular object.

In this chapter, forces are drawn concurrently (i.e. from the same point on the object) and should show which force acts in which direction. Forces can be drawn to scale, but this is often not practical and can introduce the possibility of measuring error. Forces have not necessarily been drawn to scale in this book, but the length of the arrows are roughly relative to the magnitude of the force. Sometimes the net force is shown alongside the diagram to indicate the direction of acceleration if the object is not in equilibrium.

When a falling apple experienced **drag**, the free-body diagram could be as shown in Figure 3.1.2.

In this example the magnitude of the drag equals the magnitude of the gravitational force (the lengths of the two vectors are the same), so there is no net force and the apple falls with constant velocity.

An example of a free-body diagram of a remote-control car is shown to the left (Figure 3.1.3). The diagram shows four forces (gravitational force, F_g, normal force, F_N, **frictional force**, F_f, and **applied force**, F_A) acting on the car. The gravitational force and normal force are equal and opposite, so do not cause any acceleration up or down. There is a net force to the left, meaning the applied force is greater than the frictional force.

> In a free-body diagram only forces that directly affect the object are shown. These add up to give the net force on the object.
>
> The net force, in turn, then determines the acceleration of the object using the second law of motion, $F = ma$.

> Drag and friction are forces that oppose the motion of the object. Drag acts to slow the motion of an object as it travels through air or a liquid. Frictional forces act to resist motion when two surfaces are in contact.

> It is usually clear from the context whether something is a vector. Nonetheless, vectors can be represented using vector notation. In this book vectors are represented using italics, e.g. F, as are other variables and physical quantities. You might see a different type of vector notation in books and journals. This may include bold italics, such as $\boldsymbol{F}$, or a tilde or arrow above the letter such as $\tilde{F}$ or $\vec{F}$.

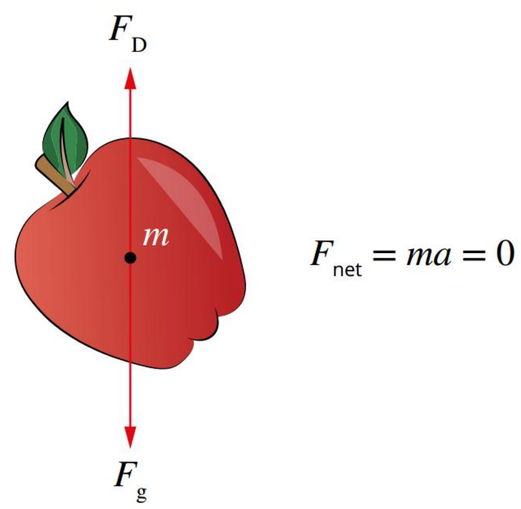


FIGURE 3.1.2 A free-body diagram showing a falling apple with drag. In this example the drag is equal in magnitude to the gravitational force so there is no net force and the apple falls with constant velocity.

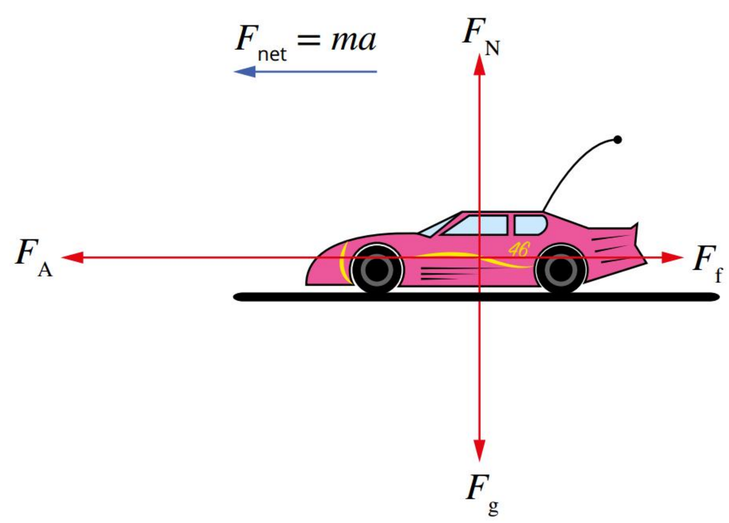


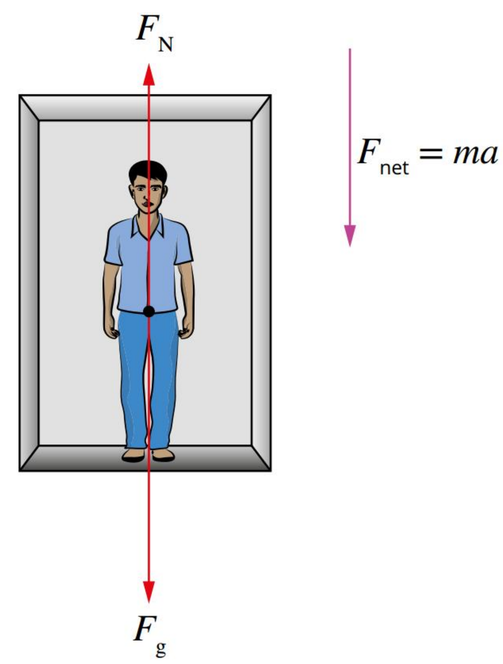
FIGURE 3.1.3 This free-body diagram of a remote-controlled car shows four forces acting (force due to gravity, normal force, friction and applied force) to give a net force to the left.

Worked example 3.1.1

FREE-BODY DIAGRAMS

A 78.0 kg student is standing in a lift on the fifth floor of a building. The lift accelerates downwards at $0.540\,\text{m}\,\text{s}^{-2}$.

a Draw a free-body diagram showing the forces that act on the student as the lift accelerates downwards.

Thinking	Working
There are two forces acting on the student: gravitational force and normal force. They are drawn parallel to each other, with the net force acting downwards.	

b Calculate the normal force the student experiences as the lift accelerates downwards.

Thinking	Working
There are two values given and these are mass and acceleration.	$m = 78.0\,\text{kg}$ $a = 0.540\,\text{m}\,\text{s}^{-2}$ downwards
Use the second law of motion to calculate the net force. As acceleration is downwards, F_g is greater than F_N.	$F_{net} = F_g - F_N$ $ma = F_g - F_N$
Calculate the gravitational force.	$F_g = mg$ $= 78.0 \times 9.8$ $= 764.4\,\text{N}$
Substitute the known vales to find F_N.	$ma = F_g - F_N$ $78.0 \times 0.540 = 764.4 - F_N$ $42.12 = 764.4 - F_N$ $-F_N = 42.12 - 764.4$ $F_N = 722\,\text{N}$
Write the normal force as a vector with magnitude and direction.	$F_N = 722\,\text{N}$ upwards

➤ Try yourself 3.1.1

FREE-BODY DIAGRAMS

A 66.0 kg student is standing in a lift on the ground floor of a building. The student presses the button marked '2' to go up to the second floor. The lift accelerates upwards at $0.820\,\text{m}\,\text{s}^{-2}$ for a few seconds before it then moves at a constant velocity.

a Draw a free-body diagram showing the forces that act on the student as the lift accelerates upwards.

b Calculate the normal force the student experiences as the lift accelerates upwards.

INCLINED PLANES

If an object such as a crate is on the ground, but the ground itself is at an angle to the horizontal, the gravitational force will still act straight down, and the normal force still acts perpendicular to the surface.

In this case the gravitational force and normal force are no longer parallel, and the magnitude of the normal force is no longer equal to the magnitude of the gravitational force. The magnitude of the gravitational force still has a negative value as its direction is straight down, but the normal force is no longer straight up.

In this situation, the crate can either be at rest, moving with a constant velocity, or accelerating along an **inclined plane**. All the laws of motion still apply, that is, the net force acting on the crate is equal to the mass of the crate multiplied by the acceleration of the crate. If the net force acting on the crate is zero, then the crate will be stationary or moving at a constant velocity.

As the angle that the inclined plane makes with the horizontal increases, the normal force decreases. This is because there is a smaller and smaller force pushing perpendicular to the surface when the plane is at an angle to the horizontal. The normal force is zero when the plane is perpendicular to the horizontal (Figure 3.1.4).

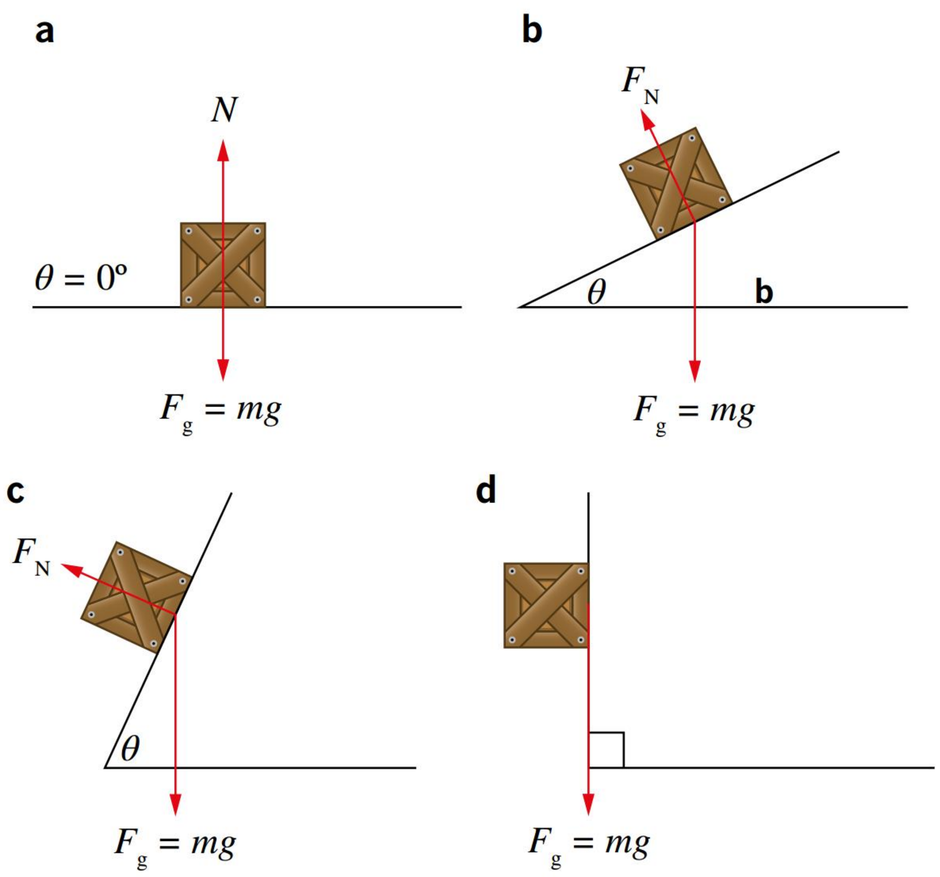


FIGURE 3.1.4 As the angle to the horizontal increases from 0° in (a), the magnitude and direction of the normal force changes, as in (b) and (c), until it is zero when the inclined plane is 90° to the horizontal. In all cases, the normal force is always perpendicular to the inclined plane.

In drawing free-body diagrams of objects on inclined planes, all forces are written according to a set of axes that are either parallel (the x-direction) or perpendicular (the y-direction) to the inclined plane. In defining the axes this way, only the gravitational force will need to be separated into components, as the normal force will always be perpendicular to the plane and any frictional forces will always act parallel to the plane (since the object's motion will either be up or down the incline).

To find the value of the normal force, the gravitational force must be separated into components:

- F_{gy}, the component of F_g perpendicular to the plane (which will be equal in magnitude and opposite in direction to the normal force)
- F_{gx}, the component of F_g parallel to the plane.

These components are shown as a right-angled triangle in Figure 3.1.5 and with the full system of forces in Figure 3.1.6.

Note that the angle formed between the gravitational force and the component of the gravitational force perpendicular to the plane is the same as the angle the inclined plane makes with the horizontal.

> The normal force is still perpendicular to the surface even if the surface is not horizontal.
>
> The force due to gravity is still straight down even if the surface is not horizontal.

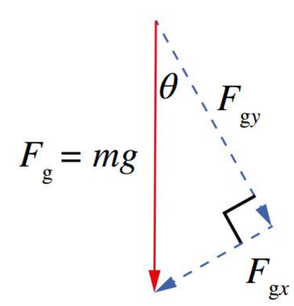


FIGURE 3.1.5 The components of gravitational force parallel (F_{gx}) and perpendicular (F_{gy}) to the inclined plane are shown as blue dashed lines. These vectors make a right-angled triangle, with the gravitational force (F_g) as the hypotenuse.

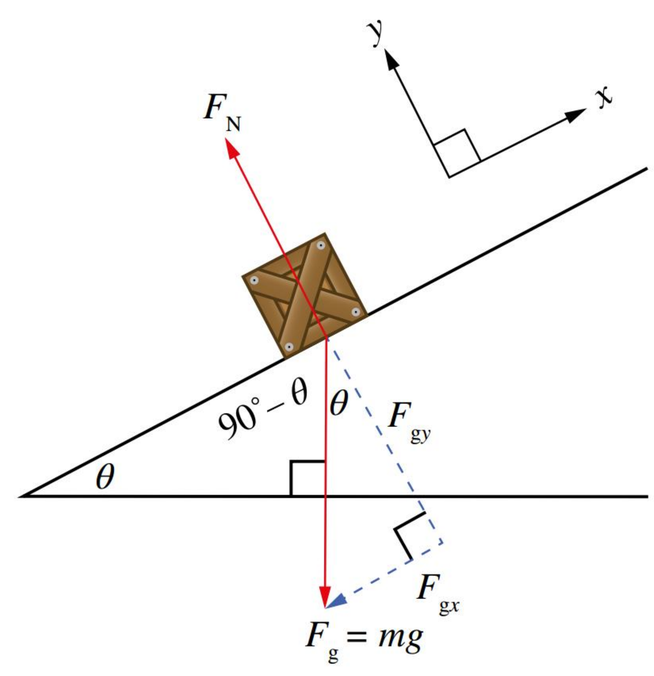


FIGURE 3.1.6 The angle formed between the gravitational force and the component of the gravitational force perpendicular to the plane is the same as the angle the inclined plane makes with the horizontal.

The components of the gravitational force can be calculated using trigonometry:

$$\cos\theta = \frac{\text{adjacent}}{\text{hypotenuse}} = \frac{F_{gy}}{F_g}$$

or

$$F_{gy} = F_g \cos\theta$$

Using the definition of gravitational force as $F_g = mg$, we can now write F_{gy} as:

$$F_{gy} = mg\cos\theta$$

and as this vector is parallel to the normal force, it must be equal in magnitude to the normal force:

$$F_N = F_{gy} = mg\cos\theta$$

The component of gravitational force acting parallel to the plane, F_{gx}, is found using sine of θ in a similar way to give:

$$F_{gx} = F_g \sin\theta$$

The normal force, F_N, and the component of gravitational force *perpendicular* to the plane, F_{gy}, are the only forces that act perpendicular to the plane and are balanced. Since they are equal, the net force will not be perpendicular to the inclined plane. The component of the gravitational force *parallel* to the plane, F_{gx}, is not balanced, so, unless there is another force acting parallel to the plane, the crate will accelerate down the plane.

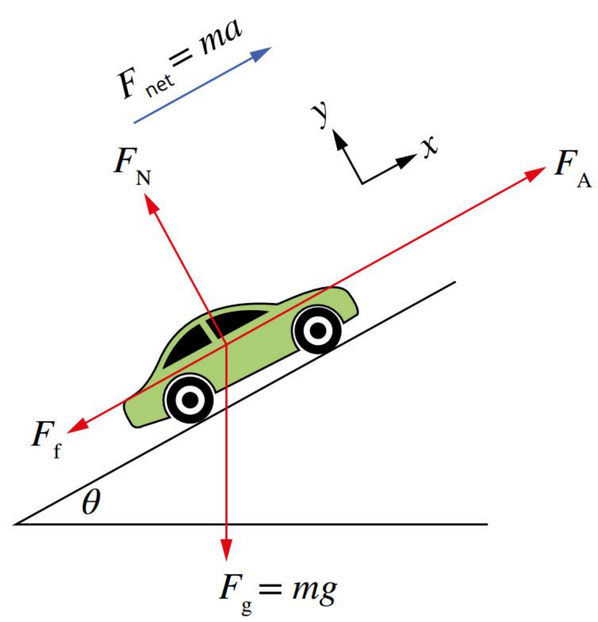


FIGURE 3.1.7 A full free-body diagram showing all the typical forces acting on an object that is accelerating up an inclined plane. All forces, except the gravitational force, act directly along either the *x*- or *y*-axes shown in the top right corner.

Typically, there are at least two other forces acting on an object on an inclined plane and they are the applied force (if the object has an engine or can supply a force that helps the object to move in a forward direction) and friction (which always opposes the motion of the object). These are added to the inclined plane force diagram to show the forces acting on a car accelerating up the plane (Figure 3.1.7).

The applied force and friction do not need to have their components resolved because they are already parallel to the inclined plane, that is, along the *x*-axis. In all situations, unless otherwise stated, the direction of acceleration (if any), will only be up or down the incline, not at an angle into the plane or out of the plane.

Brief descriptions of the common forces that can act on an object are shown in Table 3.1.1.

TABLE 3.1.1 Summary of the common forces that act on an object

Type of force	Symbol	Description	Where it acts
applied force	F_A	the force given to an object by an external push or pull, such as an engine	in the same direction as the push or pull
gravitational force	F_g or W	the force on an object due to the presence of a gravitational field	always straight down on the surface of Earth towards the centre of Earth
normal force	F_N or N	the force on an object that is due to the contact between the object and the surface it is touching. The surface pushes back on the object due to the third law of motion.	always perpendicular to the surface the object sits on
frictional force	F_f	the force on an object that opposes the motion of the object	always opposite to the direction of motion
tension	F_T or T	the force that acts along a string or wire when it is pulled tightly by forces at either end. It acts equally at all points in the string or wire.	along the string or wire, but away from the object
drag	F_D or D	air resistance, or the retarding force on an object due to its motion through a gas or liquid	always opposite to the direction of motion

Strategies for solving inclined plane problems

The following summarises strategies for solving inclined plane problems:

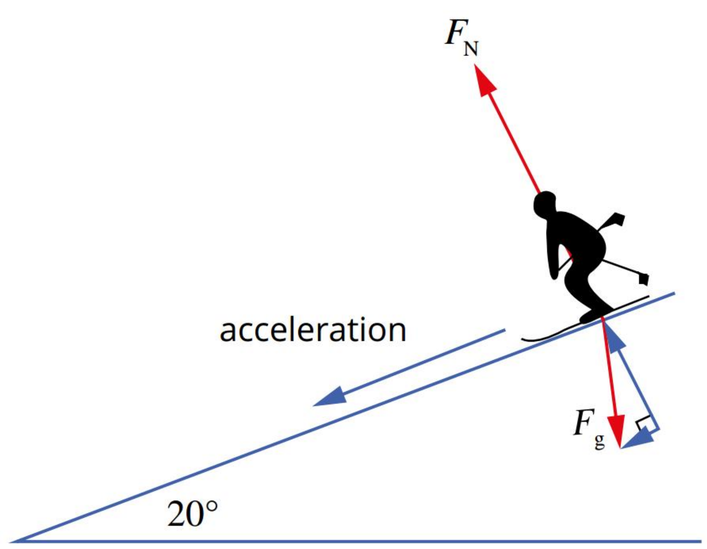
- List the information you are given.
- Draw a free-body diagram.
- Label each force acting on the mass (see Table 3.1.1).

- If the mass is accelerating, then there will be a net force in the direction of this acceleration.
- If the mass is not accelerating, then there will be zero net force.
- Remember that the net or resultant force is equal to the sum of all forces acting on the mass.
- Gravitational force is typically the only force that requires its components to be resolved perpendicular and parallel to the incline. Use trigonometry to calculate these components.
- A question might ask for the final velocity, time or displacement of the mass moving along the inclined plane. Refer to *Pearson Physics Queensland Units 1 & 2* for the equations of motion with uniform acceleration to calculate these values.

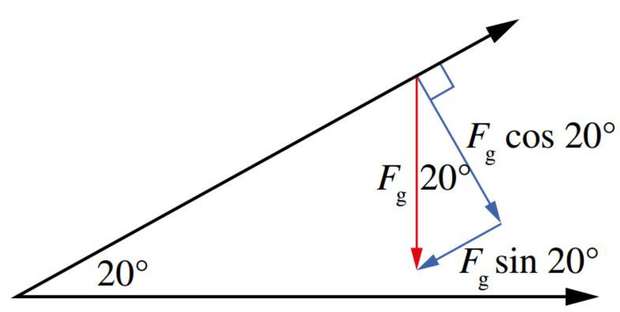
Worked example 3.1.2

INCLINED PLANES I

A skier of mass 50.0 kg is skiing freely down an icy slope that is inclined at 20.0° to the horizontal. Assume that friction is negligible and that the acceleration due to gravity is 9.8 m s^{-2}.



a Determine the components of the gravitational force of the skier perpendicular to the slope and parallel to the slope.

Thinking	Working
The components of the gravitational force perpendicular and parallel to the slope are given by trigonometric equations.	
Calculate the gravitational force of the skier.	$F_g = mg$ $= 50.0 \times 9.8$ $= 490$ N down
F_{gx} is the component of the gravitational force parallel to the slope.	$F_{gx} = F_g \sin 20.0°$ $= 490 \sin 20.0°$ $F_{gx} = 167.6 = 168$ N down (parallel to the slope)
F_{gy} is the component of the gravitational force perpendicular to the slope.	$F_{gy} = F_g \cos 20.0°$ $= 490 \cos 20.0°$ $F_{gy} = 460$ N down (perpendicular to the slope)

b Determine the normal force acting on the skier.	
Thinking	**Working**
The normal force is equal in magnitude but opposite in direction to F_{gy}.	$F_N = -F_{gy} = 460\,\text{N}$ up (perpendicular to the slope)
c Calculate the acceleration of the skier down the slope.	
Thinking	**Working**
The net force is down the slope, so this will be equal to the sum of all forces acting parallel to the slope. The acceleration is then equal to the net force divided by the mass of the skier.	$a = \frac{F_{net}}{m}$ $a = \frac{F_{net}}{m} = \frac{F_{gx}}{m} = \frac{167.6}{50.0} = 3.35$ $a = 3.35\,\text{m s}^{-2}$ down the slope

➤ Try yourself 3.1.2

INCLINED PLANES I

A skier of mass 85.0 kg is skiing freely down an icy slope that is inclined at 20.0° to the horizontal. Assume that friction is negligible and that the acceleration due to gravity is $9.8\,\text{m s}^{-2}$.

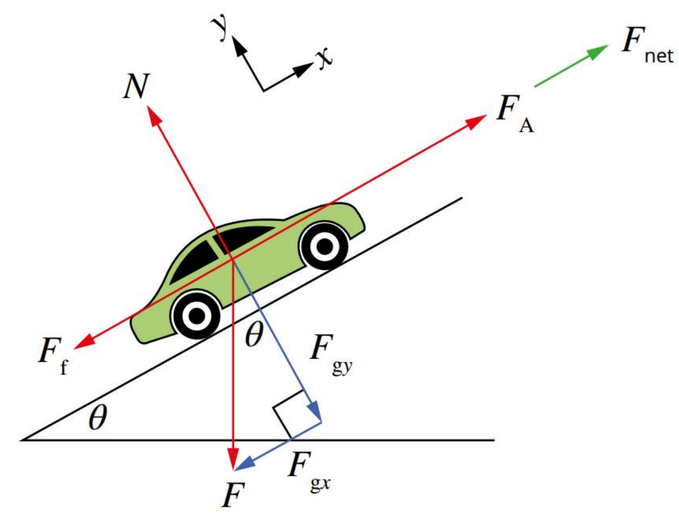
a Determine the components of gravitational force of the skier perpendicular to the slope and parallel to the slope.

b Determine the normal force acting on the skier.

c Calculate the acceleration of the skier down the slope.

Worked example 3.1.3

INCLINED PLANES II

An 850.0 kg car is accelerating up a road with a slope of 12.0° at $0.25\,\text{m s}^{-2}$. Calculate the force the engine provides to the car if the frictional forces on the car add to 500.0 N. Take g as $9.8\,\text{m s}^{-2}$.	
Thinking	**Working**
Draw a diagram of the car on the inclined plane showing all the forces acting on it. For calculations, take forces down the slope as negative and forces up the slope as positive.	
Calculate the component of the gravitational force acting parallel to the slope, F_{gx}.	$F_{gx} = F_g \sin 12.0°$ $= 850.0 \times 9.8 \times \sin 12.0°$ $F_{gx} = 1732\,\text{N}$ down the slope
Use the second law of motion to determine all forces acting parallel to the slope.	$F_{net} = ma = F_A - F_f - F_{gy}$

Substitute the values for m, a, F_f and F_{gx}.	$F_{net} = ma = F_A - F_f - F_{gy}$ $= 850.0 \times 0.25 = F_A - 500.0 - 1732$ $F_A = 212.5 + 1732 + 500.0$ $= 2444\,\text{N} = 2.4 \times 10^3\,\text{N}$
Write the applied force as a vector with magnitude and direction.	F_A, the applied force, is 2.4×10^3 N up the slope.

➤ Try yourself 3.1.3

INCLINED PLANES II

Calculate the acceleration of the car if the same car turns around and is now accelerating down the slope with the same frictional force and applied forces acting.

Take g as $9.8\,\text{m}\,\text{s}^{-2}$.

3.1 Review

SUMMARY

- The force due to gravity, F_g, of an object acts straight down in all situations.
- A normal force, F_N, acts between an object and a surface, at right angles to the surface.
- The component of the gravitational force on an inclined plane acting parallel or perpendicular to the plane can be determined using trigonometry.
- On a horizontal surface, $F_N = -F_g$ and the object is not accelerating if there are no other forces present.
- On an inclined plane, F_N is equal and opposite to the component of the gravitational force acting perpendicular to the plane F_{gy}.
- A free-body diagram shows all the forces acting on a single object.
- Vectors are used to analyse the net force acting on an object on an inclined plane.

KEY QUESTIONS

Describe

1 Name the unit of gravitational force.

2 Identify the direction in which the gravitational force of an object acts.

3 Identify the direction in which the normal force acts.

4 Identify the relationship between the magnitude of the normal force on an inclined plane as the angle to the horizontal increases.

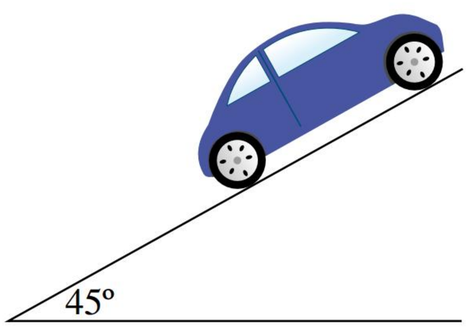
Apply

5 Explain why an object must be in contact with a surface for a normal force to exist.

6 Contrast how the normal force for objects on an inclined plane differs from that on horizontal surfaces.

7 Explain whether the gravitational force balances with the normal force on inclined planes.

8 In 2009 in Wisconsin, USA, a car stalled and became stuck on a drawbridge while the drawbridge rose to an angle of 45° (see below). The frictional force between the car's tyres and the road stopped it from rolling down the drawbridge.



Describe how the car's gravitational force, normal force and frictional force acting on the tyres of the car changed as the drawbridge rose. (Apparently the driver, uninjured, waited until the bridge came back down and drove off as if nothing had happened.)

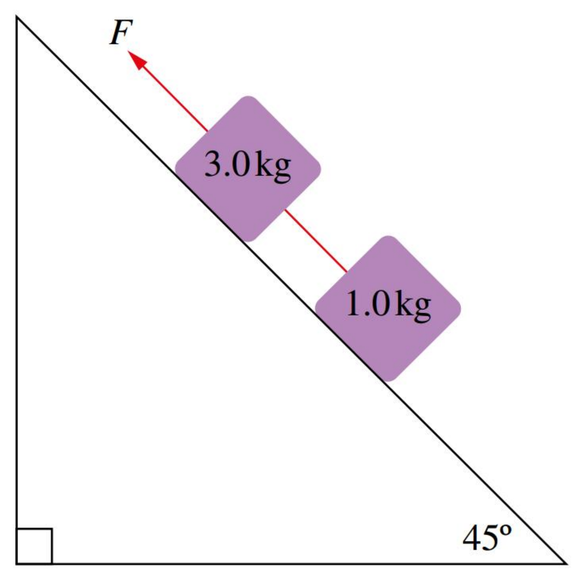
Analyse

9 Calculate the normal force acting on a skateboarder with a combined mass of 65.0 kg on a 25.0° incline.

10 Calculate the net force acting on a snowboarder with a combined mass of 88.0 kg travelling down a frictionless slope 12.5° to the horizontal.

11 Determine the force the engine must be applying to a 35 000 kg fully loaded bus being driven at a constant velocity up a 5.1° slope, if frictional forces add to 1600 N. Draw a free-body diagram to support your understanding.

12 Two masses, 1.0 kg and 3.0 kg, are tied together with a light rope and pulled up a 45° frictionless incline with a force F, as shown below.
Determine the tension in the rope and the value of F if the acceleration of the system is $2.0\,m\,s^{-2}$ up the incline.



Remember that tension is a force directed along a rope or chain that is away from the object the rope or chain is supporting. Draw free-body diagrams on each block showing the directions of each force.

3.2 Circular motion

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- describe and solve problems using average speed, average velocity, period and frequency in motion around a circle
- describe uniform circular motion as the motion of an object moving around a circle with a constant speed
- differentiate between average speed and average velocity
- solve problems involving the average speed of objects undergoing uniform circular motion.

Whenever an object moves with constant speed in a circle, it is changing three quantities:

- direction of its motion
- angle from its starting position
- distance from its starting point.

UNIFORM CIRCULAR MOTION

When an object is undergoing **uniform circular motion**, as seen in the hammer throw in the Figure 3.2.1, the direction of the object's motion is constantly changing. This means that while the *speed* is constant, the *velocity* is also constantly changing.

Recall from *Pearson Physics Queensland Units 1 & 2* that:

- The **average speed** of an object is scalar and is a measure of distance over time ($m\,s^{-1}$).
- The **average velocity** of an object is a vector and is a measure of displacement over time ($m\,s^{-1}$).
- The **period** is the total time taken for a full revolution (s).
- The **frequency** is the number of revolutions per second (s^{-1} or Hz).

  For an object travelling in a circle, the circumference is calculated using $2\pi r$.

  Recall that period (T) and frequency (f) are related by the rule:

$$f = \frac{1}{T}$$

Some examples of objects that have different average speeds of rotation are shown in Figures 3.2.2 and 3.2.3.

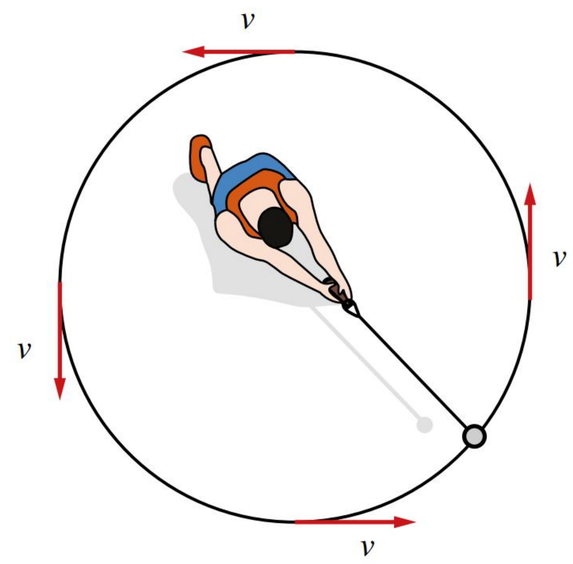


FIGURE 3.2.1 When an object undergoes uniform circular motion, the velocity is constantly changing.

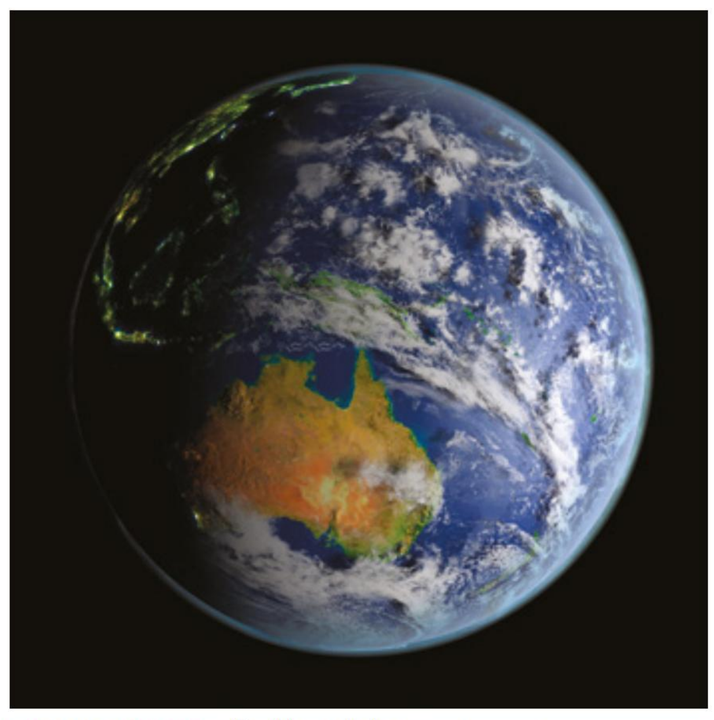


FIGURE 3.2.2 Earth rotates once every 23 hours, 56 minutes and 4.1 seconds, which is a period of 86 164.1 s and a frequency of $1.160\,58 \times 10^{-5}$ Hz. At the equator, Earth rotates at about $465\,m\,s^{-1}$.

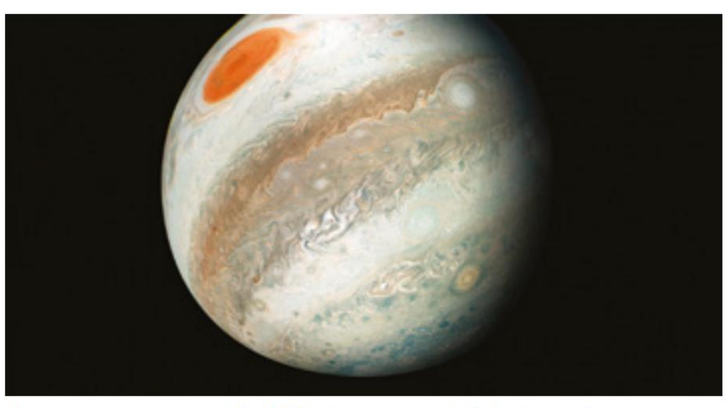


FIGURE 3.2.3 Jupiter rotates once every 9.925 hours, which is a frequency of 2.799×10^{-5} Hz. At the equator, Jupiter rotates at about $13\,km\,s^{-1}$.

The average speed of an object undergoing uniform circular motion can be calculated using:

$$v = \frac{2\pi r}{T}$$

where:

v is the average speed around the circle ($m\,s^{-1}$)

r is the radius of the circular path in (m)

T is the period of motion of the object around the circular path (s).

Units of circular motion

Note that in problems of circular motion, the rotational rate of the object is sometimes given in revolutions per minute (rpm) rather than $m\,s^{-1}$. Before any values are substituted into the formulas, the values of rotation must first be converted into $m\,s^{-1}$. Some common rotational units and their conversion factors are given in Table 3.2.1.

TABLE 3.2.1 Common units for circular motion

Unit	Symbol	Description	Is it an SI unit?	Conversion to SI unit
$m\,s^{-1}$	v	metres per second	yes	not applicable
$km\,h^{-1}$	v	kilometres per hour	no	divide by 3.6 to convert to $m\,s^{-1}$
rpm	rpm	revolutions per minute	no	divide by 60 to convert to frequency (Hz)
rps	rps	revolutions per second	no	same as frequency (Hz)
period	T	time for one revolution	yes	not applicable
frequency	f	how many revolutions per second	yes	not applicable

FIGURE 3.2.4 Formula 1 cars have engines that rotate at a maximum of 15 000 rpm.

Revolutions per minute are very commonly used to describe the rotational speeds of engines and motors. Since 2014, Formula 1 cars (Figure 3.2.4) can only use engines that are limited to 15 000 rpm. This corresponds to the piston moving inside the cylinder at 250 Hz and up to $75\,km\,h^{-1}$.

Worked example 3.2.1

UNITS OF CIRCULAR MOTION

The Windy Hill Wind Farm outside of Ravenshoe on the Atherton Tablelands in Queensland produces 12 MW of electricity. There are 20 turbines on the site, and each has blades 20.0 m long that rotate at a maximum rate of 38 revolutions per minute.

a Determine the period of the motion of the blade.

Thinking	Working
Calculate the frequency by dividing the revolutions per minute by 60.	Revolutions per second $= \frac{38}{60} =$ 0.633 rps $f = 0.633\,Hz$
Calculate the period by taking the reciprocal of frequency.	$f = \frac{1}{T}$ $0.633 = \frac{1}{T}$ $T = \frac{1}{0.633} = 1.58 = 1.6\,s$

b Calculate how fast the tip of one blade is moving in $m\,s^{-1}$ and in $km\,h^{-1}$.

Thinking	Working
Calculate the circumference of the blade's motion.	$C = 2\pi r$ $= 2 \times \pi \times 20.0$ $= 125.7\,m$
The average speed is the circumference divided by the period.	$v = \frac{125.7}{1.58}$ $= 79.6\,m\,s^{-1}$
To find the average speed in $km\,h^{-1}$ multiply by 3.6.	$v = 79.6 \times 3.6 = 287\,km\,h^{-1}$

➤ Try yourself 3.2.1

UNITS OF CIRCULAR MOTION

A typical internal hard disc drive (HDD) for a desktop computer can rotate up to 7200 revolutions per minute.

a Determine the period of the HDD.

b Calculate how fast, in $m\,s^{-1}$, a point on the edge of the HDD rotates if the diameter of the HDD is 8.89 cm.

Worked example 3.2.2

AVERAGE SPEED AND PERIOD AROUND A CIRCLE

A hammer is thrown in a cage by an Olympic athlete who rotates 3.05 times each second. The total length of the athlete's arms and hammer is 2.1 m.

a Determine the period of the hammer's motion.

Thinking	Working
Calculate the period by taking the reciprocal of the frequency.	$f = \frac{1}{T}$ $3.05 = \frac{1}{T}$ $T = \frac{1}{3.05}$ $= 0.328\,s$

b Calculate the average speed of the hammer.

Thinking	Working
The average speed of the hammer is the circumference divided by the period.	$v = \frac{2\pi r}{T}$ $= \frac{2 \times \pi \times 2.1}{0.328}$ $= 40\,m\,s^{-1}$

c Calculate the average velocity of the hammer.

Thinking	Working
The average velocity of the hammer is the displacement divided by the period.	$v = \frac{s}{T}$ $= \frac{0}{0.328}$ $= 0\,m\,s^{-1}$

➤ Try yourself 3.2.2

AVERAGE SPEED AND PERIOD AROUND A CIRCLE

A hammer is being thrown in the cage by another athlete who rotates 3.60 times each second. The total length of the athlete's arms and hammer is 1.95 m.

a Calculate the period of the hammer's motion.

b Calculate the average speed of the hammer.

c Calculate the average velocity of the hammer.

3.2 Review

SUMMARY

- Uniform circular motion is the motion of an object moving around a circle with a constant speed.
- The time taken for an object to complete one revolution around a circle is called the period, T, and is measured in seconds.
- The number of complete rotations per second is called the frequency, f. Frequency is measured in hertz (Hz) and is related to period by:

$$f = \frac{1}{T}$$

- For an object moving in a circle of radius r, the average speed, v, is the circumference of the circle divided by the period:

$$v = \frac{2\pi r}{T}$$

- For an object moving in a circle, the average velocity is zero if the object starts and finishes at the same point.

KEY QUESTIONS

Describe

1 State the SI units of period, frequency, average speed and average velocity.

2 Identify the relationship between frequency and period as the period increases.

3 Describe what period measures in circular motion.

4 Describe the conditions required for 'uniform' circular motion.

Apply

5 Determine the frequency of an object rotating at 1200 rpm.

6 Contrast average speed and average velocity for an object completing one full rotation in uniform circular motion.

7 Contrast the period and frequency of an object undergoing uniform circular motion.

8 Explain how you could be changing velocity even if you are moving at a constant speed.

Analyse

9 Calculate the average speed of a cyclist who takes 44.9 s to complete one circuit of a circular track with a radius of 50 m.

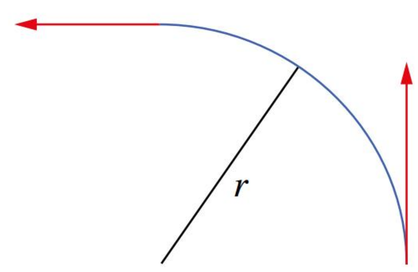
10 Calculate the length of a fan blade if the edge of the blade has an average speed of $28.3\,\mathrm{m\,s^{-1}}$ with a period of 40 ms.

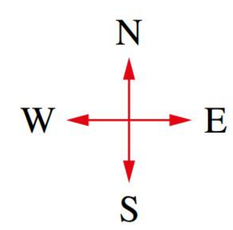
11 The Hubble Space Telescope makes an approximately circular orbit of Earth at an average altitude of 540 km above Earth's surface, and a period of 95.47 minutes. The radius of Earth is 6400 km.

a Calculate the average speed of the telescope.

b Calculate the average velocity of the telescope.

12 David takes a ride along a circularly curved track that has a radius of 1250 m as shown below. He starts the trip riding exactly due north and finishes facing due west. He travels at an average speed of $12.3\,\mathrm{km\,h^{-1}}$. Calculate the average velocity of his trip.





3.3 Centripetal force

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- recall that the velocity of an object moving in a circle is always perpendicular to the radius of the circle, i.e. at a tangent to the circle
- understand that motion around a circle involves a force that is always perpendicular to the velocity of the object
- describe centripetal acceleration as the acceleration that keeps an object moving in uniform circular motion
- describe centripetal force as the *net* force an object experiences that keeps it moving in uniform circular motion
- understand that centripetal acceleration and centripetal force are always directed towards the centre of the circle the object is moving around
- solve problems involving centripetal acceleration and centripetal force.

If the motion of an object moving in a circle were to be frozen, as in Figure 3.3.1, we would find that the velocity vector is always pointing in the direction at a tangent to its motion around the circular path, and at right angles to a line drawn to the centre of the path. The direction of the velocity shows where the object would move if the force causing it to move in a circle were to disappear.

This direction is continuously changing so that exactly one half of a rotation later the velocity vector is pointing in the opposite direction.

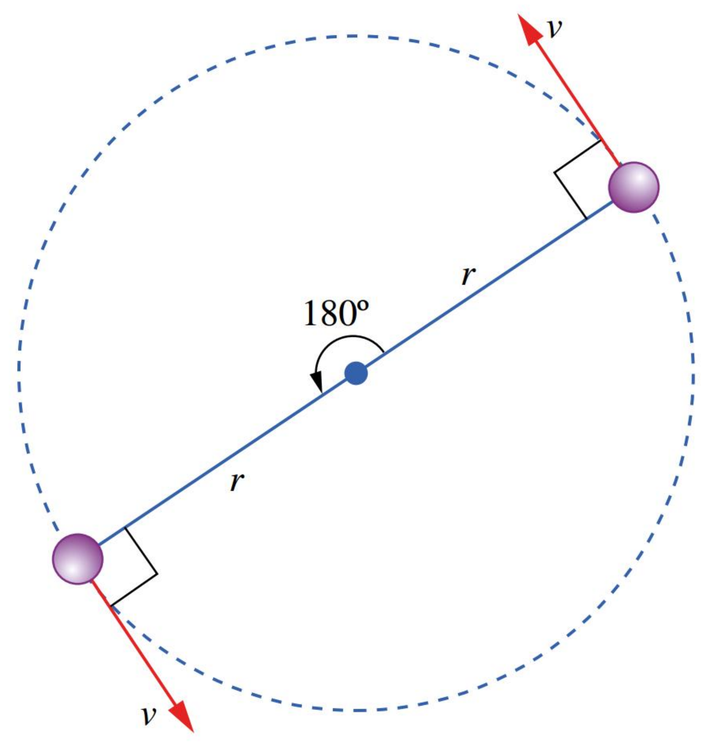


FIGURE 3.3.1 The velocity vector of an object in circular motion always points at a tangent to its direction of motion.

CENTRIPETAL ACCELERATION

Because the direction of an object in uniform circular motion is changing, the object's *velocity* is changing, but its speed is constant. So, even if an object's speed is constant, it is still accelerating because its *direction* is changing.

This acceleration, a_c, is known as **centripetal acceleration** and is the resulting, or net, acceleration of a body that is moving in a circle of radius r, with a velocity v.

The centripetal acceleration of an object moving with uniform circular motion is given by:

$$a_c = \frac{v^2}{r}$$

where:

a_c is the centripetal acceleration of the object ($m\,s^{-2}$)

v is average speed of the object ($m\,s^{-1}$)

r is the radius of the circular path in (m)

As it is a vector, centripetal acceleration requires a direction. A vector that is at right angles to a tangent must point towards the centre of the circle; hence, the direction of centripetal acceleration is directed towards the centre of the circle.

> **i** The magnitude of centripetal acceleration is $a_c = \frac{v^2}{r}$. It is directed towards the centre of the circle that the object is moving around.

No matter where the object is, if it is moving in a circle then it will have a velocity vector at a tangent to the radius and a centripetal acceleration vector pointing towards the centre of the circle as shown in Figure 3.3.2. These vectors are always at right angles to each other.

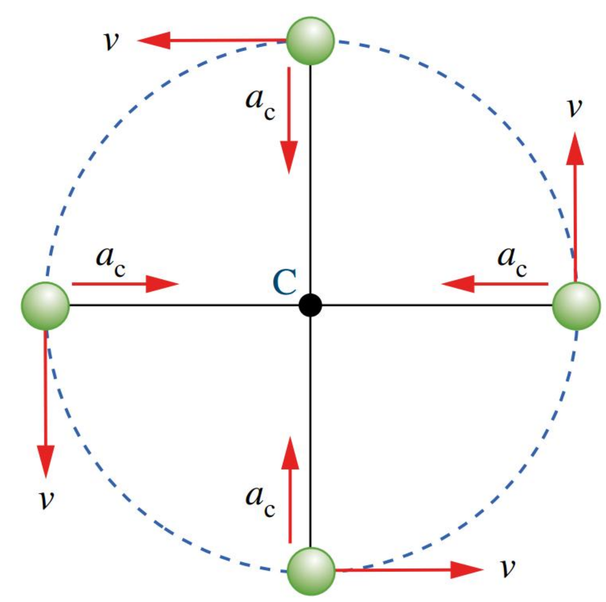


FIGURE 3.3.2 The centripetal acceleration of an object moving with uniform circular motion is always directed towards the centre of the circle, and at right angles to the object's velocity.

The magnitude of centripetal force is $F_c = F_{net} = \frac{mv^2}{r}$, and this is directed towards the centre of the circle that the object is moving around, i.e. in the same direction as the centripetal acceleration.

CENTRIPETAL FORCE

If the sum of all forces that act on an object cause it to move in a circle, then the second law of motion can be written using centripetal acceleration instead of linear acceleration.

This force is called the **centripetal force**, F_c. It is the resulting force that causes an object of mass m to move in a circle of radius r, with a velocity v.

The centripetal force, which is also the net force, acting on an object moving with uniform circular motion is given by:

$$F_c = F_{net} = \frac{mv^2}{r}$$

where:

F_c is the centripetal force acting on the object (N)

m is the mass of the object (kg)

v is average speed of the object ($m\,s^{-1}$)

r is the radius of the circular path in (m)

Like centripetal acceleration, the centripetal force is directed towards the centre of the circle the object is moving around. If the force acts on an object at right angles to its uniform motion (i.e. constant speed), then the object will be continually changing direction, hence moving in a circle.

It is important to remember that the centripetal force is the resulting, or net, force that causes the circular motion of the object. There must always be a non-zero net force acting on an object for it to move in a circle.

Examples of centripetal force in action

As a car turns a left corner, the tyres exert a frictional force on the road towards the right of the car's motion. By the third law of motion, the road must also exert a frictional force on the tyres in the opposite direction (the left) to the force exerted by the tyres on the road, causing the tyres and car to move to the left.

If the force on the road from the tyres is larger than the friction between the tyres and the road, then the tyres will lose grip and the centripetal force (i.e. net force) from the tyres disappears. As there is no net force on the tyres, there will be no force on the car and the car will continue to move at a constant velocity in a straight line rather than turning the corner (Figure 3.3.3).

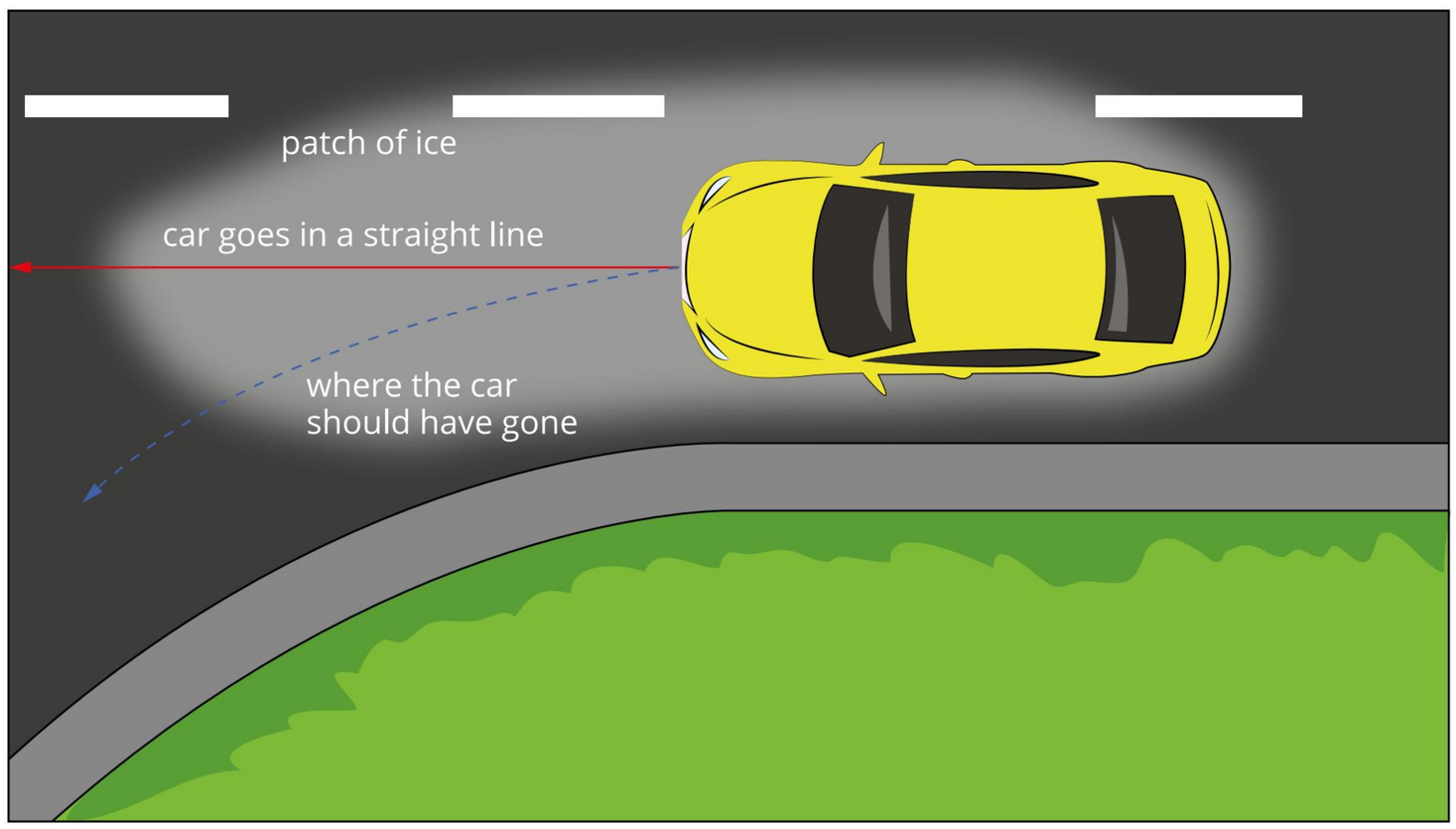


FIGURE 3.3.3 A car will skid off the road when trying to turn a corner when there is insufficient frictional force between the road and the tyres. In this case there is no centripetal force, thus the car continues to move in a straight line.

When turning a corner in a car, a rolling object may experience a 'force' pushing it outwards. This is commonly, but incorrectly, referred to as 'centrifugal force'. This force does not exist (Figure 3.3.4).

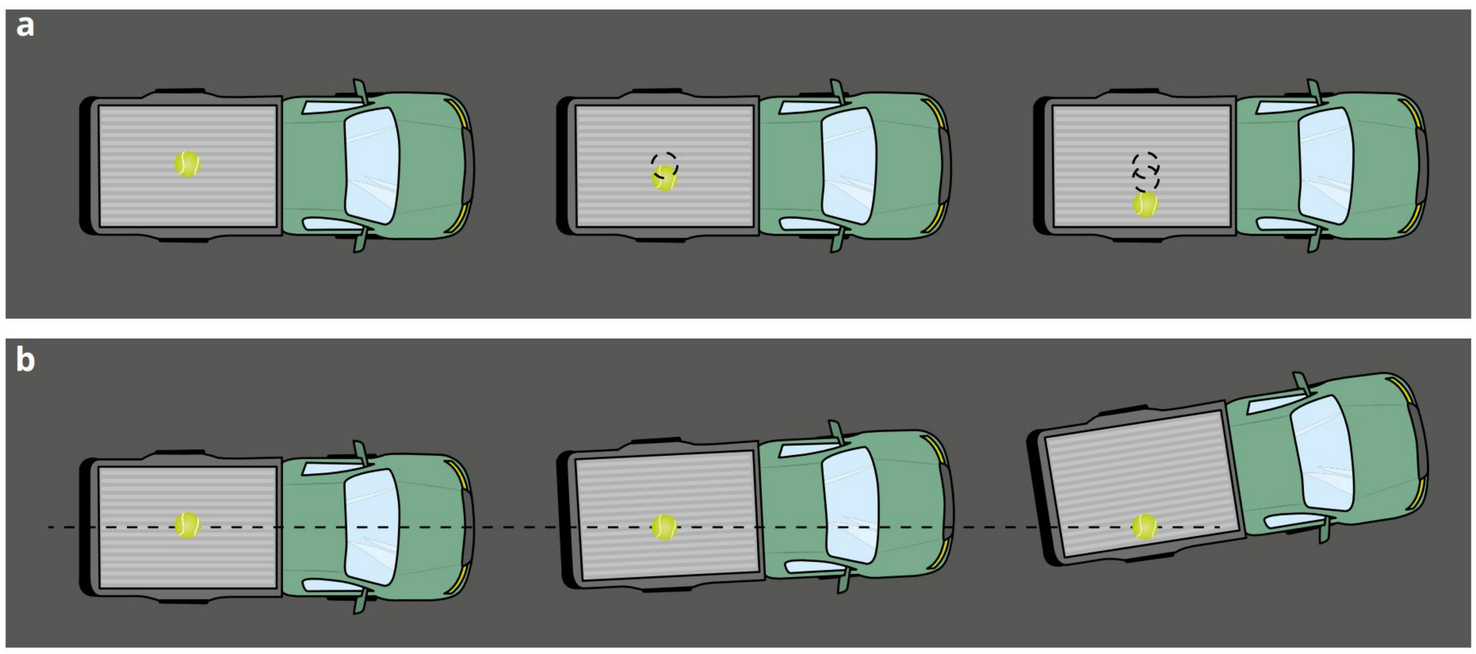


FIGURE 3.3.4 Two different points of view of a ball in the tray of a utility truck moving at a constant speed but turning left, as viewed (a) from above from the utility's point of view and (b) from the ball's point of view.

Figure 3.3.4a shows the motion of a ball in the tray of a utility truck that is turning left, from the point of view of the utility. The ball appears to violate the laws of motion, displaying a sideways force (the apparent 'centrifugal force') that is not the result of the interaction of a force with any other object. As nothing is causing this force, it does not exist. So, what is causing the apparent motion of the ball?

Figure 3.3.4b shows the motion of the ball from its own point of view, or from the point of view of an outside observer watching the utility turn the corner. In this point of view the ball obeys the first law of motion, i.e. it will move in a straight line with the same speed until an unbalanced force acts upon it. No forces are being applied to the ball, so it continues moving in a straight line, shown with the dashed line in Figure 3.3.4b. It is the truck that is being forced to move left via friction with the road, and the ball is simply hit by the right side of the utility because the utility is turning into the path of the ball. Hence, there is no need for a centrifugal force to explain the ball's motion.

Worked example 3.3.1

CENTRIPETAL FORCE AND ACCELERATION

The Moon has a mass of 7.3477×10^{22} kg and takes 27.322 days to orbit Earth at an average distance of 384 399 km.	
a Calculate the average speed of the Moon in its orbit around Earth.	
Thinking	**Working**
Convert the period and radius to SI units.	$T = 27.322 \text{ days} = 27.322 \times 24 \times 3600\,\text{s}$ $= 2\,360\,620.8\,\text{s}$ $r = 384\,399\,\text{km}$ $= 384.399 \times 10^3\,\text{m}$ $= 3.84399 \times 10^8\,\text{m}$
The average speed is the circumference of the circular orbit divided by the period.	$v = \frac{2\pi r}{T}$ $= \frac{2 \times \pi \times (3.84399 \times 10^8)}{2\,360\,620.8}$ $= 1023.14$ $= 1.0231 \times 10^3\,\text{m s}^{-1}$

b Calculate the centripetal acceleration of the Moon.	
Thinking	**Working**
Substitute the calculated value for v into the formula for centripetal acceleration.	$a_c = \frac{v^2}{r}$ $= \frac{1023.14^2}{3.84399 \times 10^8}$ $= 0.00272325$ $= 2.7233 \times 10^{-3}\,\text{m s}^{-2}$ towards Earth

c Calculate the centripetal force acting on the Moon.	
Thinking	**Working**
Recall the equation for the centripetal force, substitute the values and solve. Note that this could also be calculated using $F_c = ma_c$.	$F_c = \frac{mv^2}{r}$ $= \frac{(7.3477 \times 10^{22}) \times 1023.14^2}{3.84399 \times 10^8}$ $= 2.0010 \times 10^{20}$ N towards Earth

➤ Try yourself 3.3.1

CENTRIPETAL FORCE AND ACCELERATION

Earth has a mass of 5.97×10^{24} kg and takes exactly 1.0 year to orbit the Sun at an average distance of 150 000 000 km.

a Calculate the average speed of Earth in its orbit around the Sun.

b Calculate the centripetal acceleration of Earth.

c Calculate the centripetal force acting on Earth.

CIRCULAR MOTION IN A HORIZONTAL PLANE

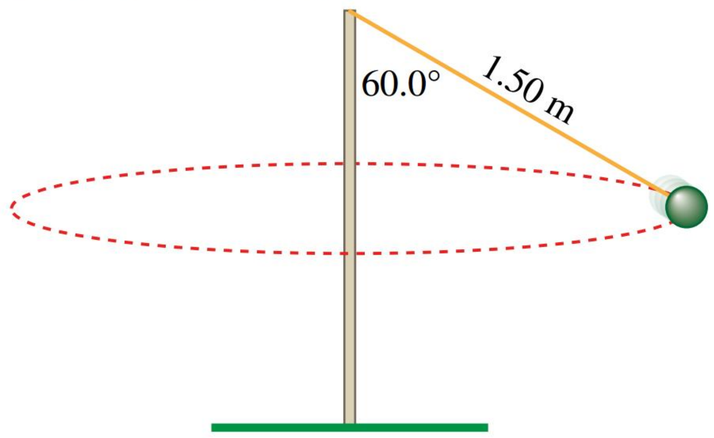
The interaction between the gravitational force, the normal force and the centripetal force on an object moving in circular motion depends on whether the object is rotating about a horizontal or a vertical plane. At every point in a horizontal plane, the centripetal force will act perpendicular to the gravitational and normal forces (Figure 3.2.2). The speed of the object will be constant, so the centripetal force will be constant.

When an object is twirled on the end of a string in a horizontal circle, it will always hang below the pivot point. If the object were to trace a horizontal circle at the same height as the pivot point, the string would be perpendicular to the direction of the object's gravitational force, and there would be no component of tension in the string in the vertical direction to balance the gravitational force of the object. Therefore, the object traces a circle lower than the pivot point, and has both vertical and horizontal components. The vertical component balances the gravitational force of the object, and the horizontal component provides the centripetal force to keep the object moving in a circle. The tension in the string is therefore greater than the centripetal force keeping the object moving in a circle.

Worked example 3.3.2

HORIZONTAL CENTRIPETAL FORCE AND ACCELERATION

During a game of totem tennis, a 150 g tennis ball is swinging freely in a horizontal circular path as shown below.

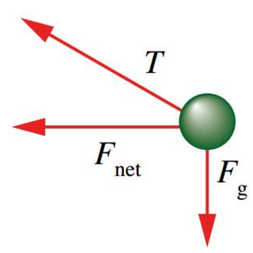


The cord is 1.50 m long and is at an angle of 60.0° to the vertical.

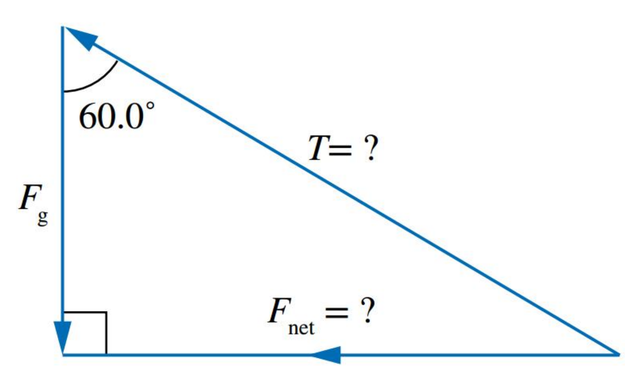
a Calculate the radius of the ball's circular path.

Thinking	Working
Use an appropriate trigonometric ratio to determine the radius of the ball's path.	$\sin 60.0° = \frac{r}{1.50}$ $r = 1.50 \sin 60.0°$ $= 1.30\,\text{m}$

b Sketch a free-body diagram showing all the forces acting on the ball.

Thinking	Working
Forces that act on the ball are the tension in the string and the gravitational force of the ball. Centripetal force ($F_c = F_{net}$) is the sum of the tension and the gravitational force of the ball.	

c Determine the net force acting on the ball.

Thinking	Working
The net force on the ball is equal to the sum of the gravitational force and the tension in the string. This gives a vector acting directly to the left which is the centripetal force, since the ball is moving in a circle.	
Calculate the gravitational force first.	$F_g = mg = 0.150 \times 9.8$ $= 1.47\,\text{N}$ straight down
Using trigonometry and the vertical and horizontal components of the tension, the net force can be calculated. Note that that centripetal force cannot be directly calculated using the formula for centripetal force because neither the speed nor period are known.	$\tan 60.0° = \frac{F_{net}}{F_g}$ $F_{net} = F_g \tan 60.0°$ $= 1.47 \tan 60.0°$ $= 2.55\,\text{N}$ towards the pole

d Calculate the tension in the string.	
Thinking	**Working**
The tension in the string can also be found using the force triangle in part **c**, using either the vertical or horizontal component of the tension.	$\cos 60.0° = \frac{F_g}{T}$ $T = \frac{F_g}{\cos 60.0°} = \frac{1.47}{\cos 60.0°}$ $T = 2.94\,\text{N}$ along the cord towards the top of the pole. or $\sin 60.0° = \frac{F_{net}}{T}$ $T = \frac{F_{net}}{\sin 60.0°} = \frac{2.55}{\sin 60.0°}$ $T = 2.94\,\text{N}$ along the cord towards the top of the pole.

e Calculate the speed of the ball.	
Thinking	**Working**
The speed of the ball can be found using the formula for centripetal force.	$F_c = \frac{mv^2}{r} = 2.55$ $v = \sqrt{\frac{2.55 \times 1.30}{0.150}} = 4.70\,\text{m s}^{-1}$

➤ Try yourself 3.3.2

HORIZONTAL CENTRIPETAL FORCE AND ACCELERATION

The ball on the totem tennis pole is swapped with a slightly heavier ball with a mass of 175 g. The same 1.50 m cord is used which is now swung 50.0° to the vertical.

a Calculate the radius of the ball's circular path.

b Sketch a free-body diagram showing all the forces acting on the ball.

c Determine the net force acting on the ball.

d Calculate the tension in the string.

e Calculate the speed of the ball.

3.3 Review

SUMMARY

- The direction of centripetal acceleration is always towards the centre of the circle the object is moving around.
- The centripetal force, F_c, is the *net* force an object of mass m experiences that keeps it moving in uniform circular motion with speed, v, and radius r:

$$F_c = \frac{mv^2}{r}$$

- Centripetal force is also always directed towards the centre of the circle the object is moving around.
- The magnitude of centripetal acceleration is $a_c = \frac{v^2}{r}$

KEY QUESTIONS

Describe

1 State the direction of the velocity vector of an object that moves in a circle.

2 State the direction in which centripetal acceleration acts.

3 Describe the relationship that must exist between the net force and the velocity of a moving mass for uniform circular motion to result.

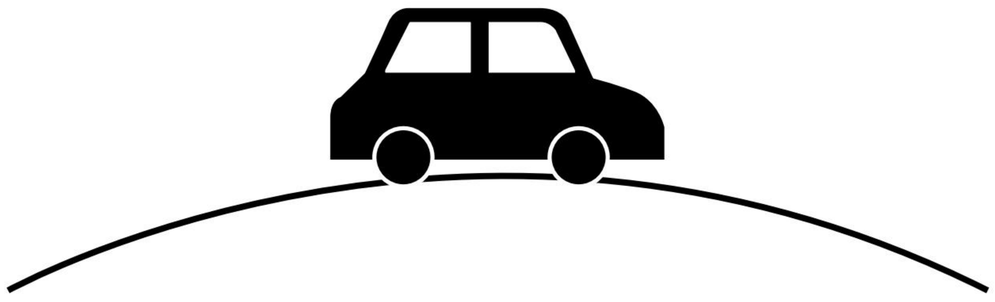
4 Recall the formula used to calculate centripetal acceleration using the velocity and radius of the circular path.

Apply

5 Explain why the centripetal force is not necessarily a force that acts directly on an object moving in a circle.

6 Identify at which point in their rotation hammer and discus throwers need to release their projectiles in order for the projectile to land on the arena.

7 A car is travelling over the top of a hill that models uniform circular motion.



Draw an arrow that represents the direction of the net force acting on the car. Explain your reasoning.

8 Explain why a tighter (smaller radius) turn results in more centripetal force for a car moving at the same speed.

Analyse

9 A student is swinging a cork on a string horizontally above their head. The cork experiences a tension force of 2.5 N from the string. The student keeps the length of string the same but doubles the speed of rotation. Determine the tension force from the string when the cork is spun at the new speed.

10 Calculate the magnitude of the centripetal acceleration of a person standing on the surface of Earth at the equator. Use the radius of Earth at the equator as 6378 km.

11 A car of mass 750 kg is travelling around a roundabout with a 5.0 m radius. They are driving with a speed of $4.0\,\mathrm{m\,s^{-1}}$. Calculate the net force experienced by the car as it travels around the roundabout.

12 A cyclotron is a device used to accelerate subatomic particles to very high speeds for them to collide and create new particles. The cyclotron consists of an electromagnet and a circular tube for the particles to move along. Calculate the speed of the protons if the electromagnet exerts a force of 7.50×10^{-13} N on a beam of protons, causing them to move in a circular path of radius 1.20 m. The mass of a proton is 1.67×10^{-27} kg.

Chapter review

03

KEY TERMS

acceleration due to gravity
applied force
average speed
average velocity
centripetal acceleration
centripetal force
drag
force
force due to gravity
free-body diagram
frequency
frictional force
gravitational force
inclined plane
normal force
period
tension
uniform circular motion
weight

KEY QUESTIONS

Describe

1 Identify the situation in which gravitational force is equal to the normal force.

A in all situations
B when the surface is at 0° to the horizontal
C when the surface is at 45° to the horizontal
D when the surface is at 90° to the horizontal

2 Identify the option that best describes the motion of a rubber ball rolling down a slope on which friction is negligible.

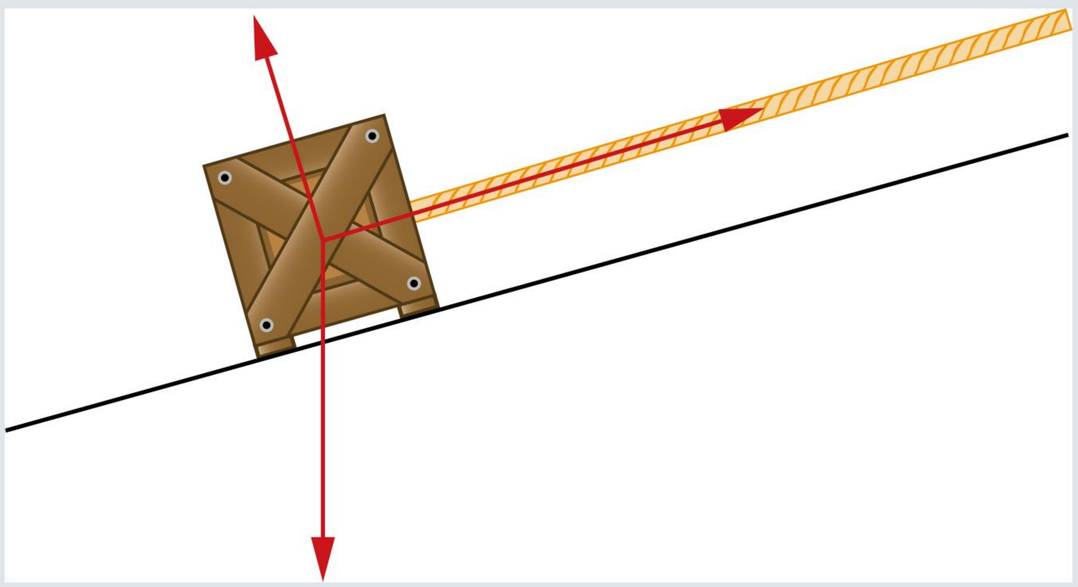
A It moves with constant velocity.
B It moves with constant acceleration.
C It moves with increasing acceleration.
D It moves with decreasing acceleration.

3 Identify the formula that correctly describes the magnitude of centripetal force.

A $F_c = \frac{mr^2}{v}$
B $F_c = \frac{mv^2}{2}$
C $F_c = \frac{mv}{r}$
D $F_c = \frac{mv^2}{r}$

4 State in which direction friction acts on an object moving down an incline plane.

5 A heavy crate is being pulled up a ramp by a strong rope. On the diagram below, label the tension force, the normal force and the gravitational force acting on the crate.



6 Describe the relationship between the normal force and gravitational forces acting on an object at rest on an incline plane.

7 State how the speed of an object changes as it moves in uniform circular motion.

8 State the unit used to measure period.

9 Identify what two values you need to calculate the average speed of an object in uniform circular motion.

10 Identify what provides the centripetal force needed to keep an object in an orbit around Earth.

Apply

11 Identify which of the following forces must balance for an object to remain stationary on an inclined plane:

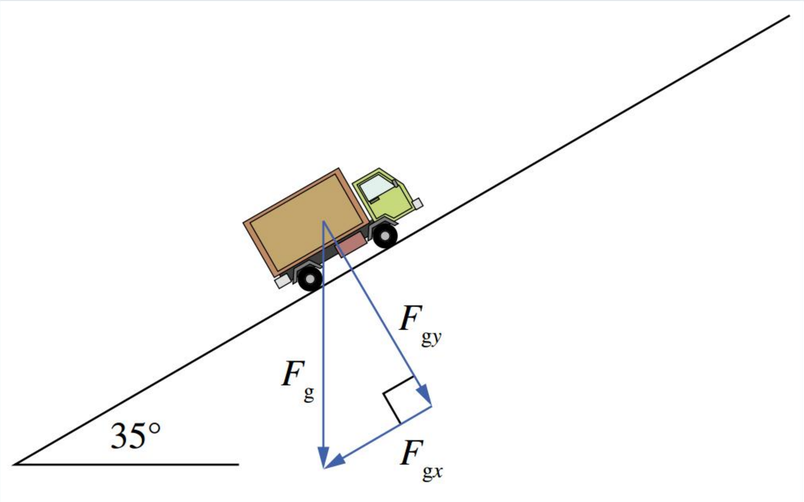
A gravitational force and normal force
B gravitational force and frictional force
C frictional force and the component of gravitational force parallel to the plane
D frictional force and the component of gravitational force perpendicular to the plane

12 Identify which of the following statements describes the forces acting on an object on a plane inclined at an angle θ, ($\theta > 0°$):

A The normal force and the gravitational force cancel out.
B The normal force is equal in magnitude to the gravitational force.
C The normal force is always perpendicular to the surface.
D In the absence of friction, a component of the normal force causes the object to accelerate down the slope.

13 A box is placed on a frictionless surface 10° to the horizontal. No external force is applied, but the box starts sliding down the slope. Identify the force that is causing the box to move.

14 This is a partially drawn free-body diagram of a 2.58×10^3 kg broken-down truck resting on an inclined plane at an angle of 35° to the horizontal. Only the gravitational force and its components are shown.



- **a** Describe the net force, and hence the acceleration, of the truck.
- **b** Complete the free-body diagram by drawing vectors representing the frictional force and normal force.
- **c** Calculate the magnitudes of the components of the gravitational force parallel, F_{gx}, and perpendicular, F_{gy}, to the surface of the plane.
- **d** Calculate the magnitude of the normal force acting on the truck.

15 Explain why an object in uniform circular motion is accelerating even though its speed is constant.

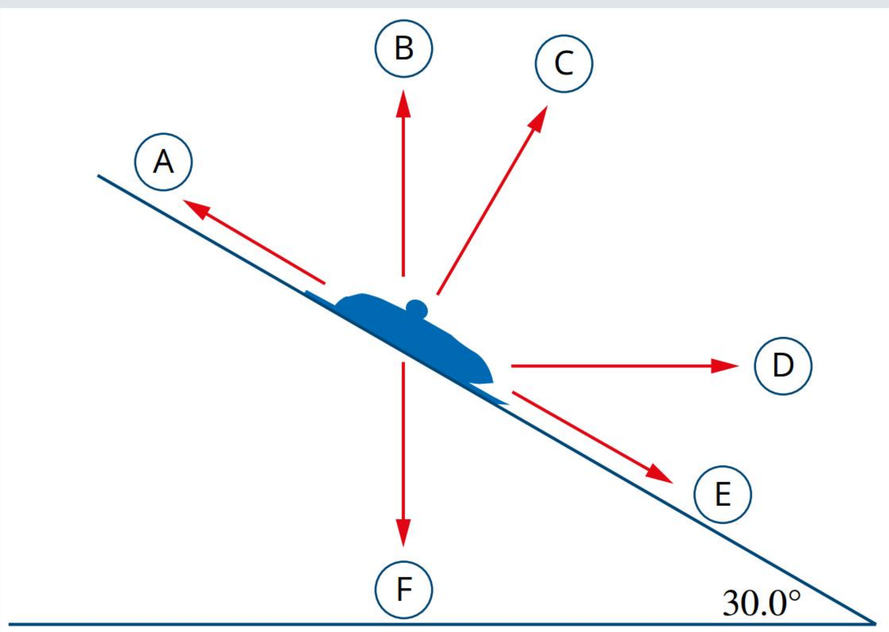
16 Identify the relationship between period and average speed of an object as the average speed increases.

17 Determine the average period of the seconds hand on a clock.

18 Explain why a hammer moves off in a straight line when the hammer thrower lets go.

Analyse

19 Penny is riding in a bobsled that is sliding down a snow-covered hill with a slope of 30.0°. The bobsled is frictionless in situations where brakes are not applied. The total mass of the sled and Penny is 102 kg. Initially the brakes are on and the sled moves down the hill with a constant velocity.



- **a** Determine which one of the arrows A–F best represents the direction of the frictional force acting on the sled.
- **b** Determine which one of the arrows A–F best represents the direction of the normal force acting on the sled.
- **c** Calculate the frictional force acting on the sled
- **d** Calculate the magnitude of Penny's acceleration when she releases the brakes and the sled accelerates.
- **e** Determine how the acceleration of the bobsled will be affected when Penny rides the bobsled down the same slope with an extra passenger so that its total mass is 144 kg. Penny rides with the brakes off, so friction can be ignored again.

20 Declan has a mass of 57 kg and he is riding his 3.0 kg skateboard down a 5.0 m long ramp that is inclined at an angle of 65° to the horizontal. Ignore friction when answering question parts **a**–**d**.

- **a** Calculate the magnitude of the normal force acting on Declan and his skateboard.
- **b** Determine the net force acting on Declan and his board when no friction acts.
- **c** Calculate Declan's acceleration as he travels down the ramp.
- **d** Calculate his final speed as he reaches the bottom of the ramp, if Declan's initial speed is zero at the top of the ramp.
- **e** Declan now stands halfway up the incline while holding the board in his hands. Friction now acts on Declan. Calculate the frictional force acting on Declan while he is standing stationary on the ramp.

21 Angelina twirls a 7.00 kg hammer tied to the end of a 1.3 m rope in an approximately horizontal circle. The hammer moves at a rate of 1.0 revolutions per second.

- **a** Calculate the average speed of the hammer as it travels around in its path.
- **b** Calculate the centripetal acceleration of the hammer.
- **c** Calculate the tension in the rope.

22 A turbocharger is a device that is used to increase the power and efficiency of a normal internal combustion engine. It works using a set of blades rotating at 250 000 rpm to draw air into the engine. The blades of a particular turbocharger are 6.0 cm in radius.

- **a** Calculate the frequency of the blades.
- **b** Calculate the period of the blades.
- **c** Calculate the average speed of the tip of the blades.

23 The galaxy NGC 1365, in the constellation Fornax, shown below, is thought to have a supermassive black hole in its centre. This black hole has a mass two million times the mass of the Sun and is also the fastest spinning object ever measured, rotating at 85% of the speed of light.

If the radius of the black hole is 1.6 million km and the speed of light is $3.00 \times 10^8\,\text{m s}^{-1}$:

a calculate the period of the black hole

b calculate the frequency of the black hole

c calculate the magnitude of the centripetal acceleration of the black hole.

24 A passenger riding on a very fast rollercoaster feels weightless when travelling upside down through a series of loops. Describe the forces acting on the passenger for this to occur.

Interpret

25 The highest waterslide in the world is in Brazil. It is 49.0 m tall and is inclined at an angle of 60.0° to the horizontal. It is known that riders reach a speed of $91.0\,\text{km h}^{-1}$ on this slide. Do not assume friction is negligible.

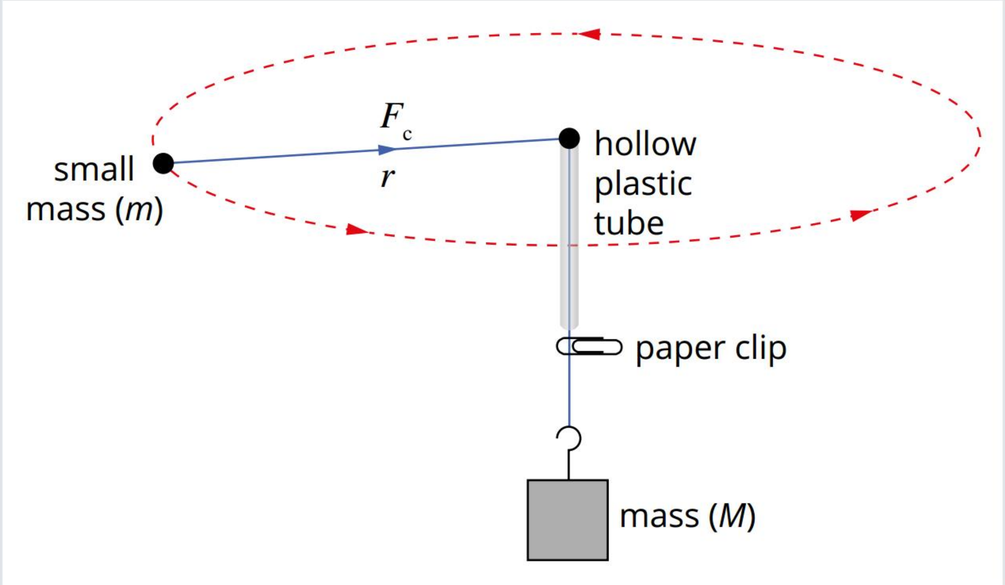
a Calculate the net force on a 70.0 kg teenager using the slide.

b Calculate the magnitude of the average frictional force opposing the teenager's motion.

c Determine the normal force acting on the teenager.

26 Rob performed an experiment to determine the value of the acceleration due to Earth's gravity, *g*. A known, but varied mass, *M*, connected to a light string was threaded through a small tube. Connected to the other end of the string was a small, but constant mass, *m*.

The small mass, *m*, was then twirled around so that the radius, *r*, of the motion was kept constant. A paperclip was attached to the string just underneath the end of the tube so the radius of the circular motion could be kept constant. This set-up is shown below.



The mass underneath the tube, *M*, was varied and the period, *T*, of one swing was recorded in the table below. The radius of the string was kept constant at 30.0 cm, and the small mass being twirled was kept constant at 50.0 g. Rob recorded the values in the table below:

Mass underneath tube, *M* (kg)	**Period of one swing, *T* (s)**
0.050	1.11
0.100	0.82
0.150	0.66
0.200	0.55
0.250	0.49
0.300	0.45

a Show that the gravitational force, *mg*, of the mass underneath the tube can be written as:

$$mg = \frac{4\pi^2 Mr}{T^2}$$

b When plotting *T* against *M*, the data demonstrates a non-linear relationship. Determine how the data can be linearised.

c Draw a graph of the new linearised data including a line of best fit.

d Use the derived formula and the gradient of the line of best fit to determine acceleration due to gravity from this investigation.

Data analysis

DATA SET 1

The information below applies to Questions **1–4**.

A student has conducted an experiment to measure acceleration due to gravity. This was completed by recording the average acceleration of blocks of ice sliding down an inclined plane. The angle of the inclined plane was increased after each trial.

The experimental data was collected and is presented in Table 1. The data was processed and is presented in Figure 1.

TABLE 1 Average time of journey and average acceleration of ice blocks released down an incline plane of varying angles.

Angle (degrees)	Average time of ice journey (s)	Average acceleration of the ice ($m\,s^{-2}$)
5.00	4.30	0.21
10.00	2.00	0.95
15.00	1.30	2.30
20.00	1.20	2.60
25.00	1.00	3.80
30.00	0.90	4.69

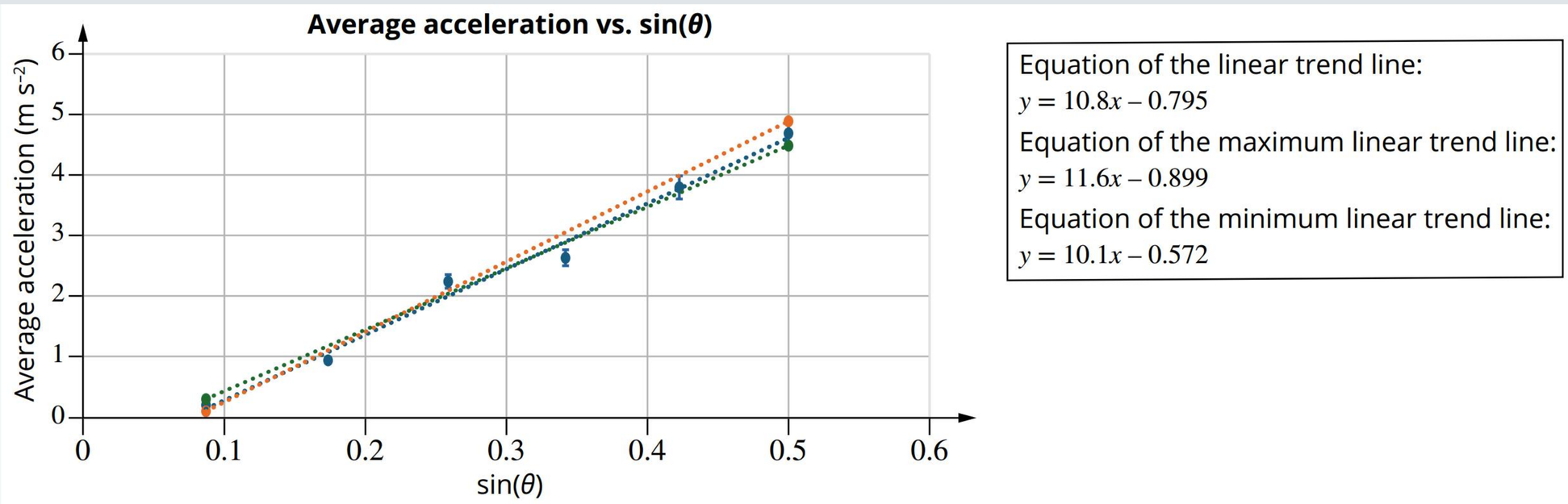


FIGURE 1 Graph of average acceleration against sine of the angle of inclination for blocks of ice released down an incline plane.

Question 1 (3 marks)

Identify the mathematical relationship between the average acceleration of the blocks of ice and the angle of inclination, including the uncertainty of the gradient and *y*-intercept.

Question 2 (1 mark)

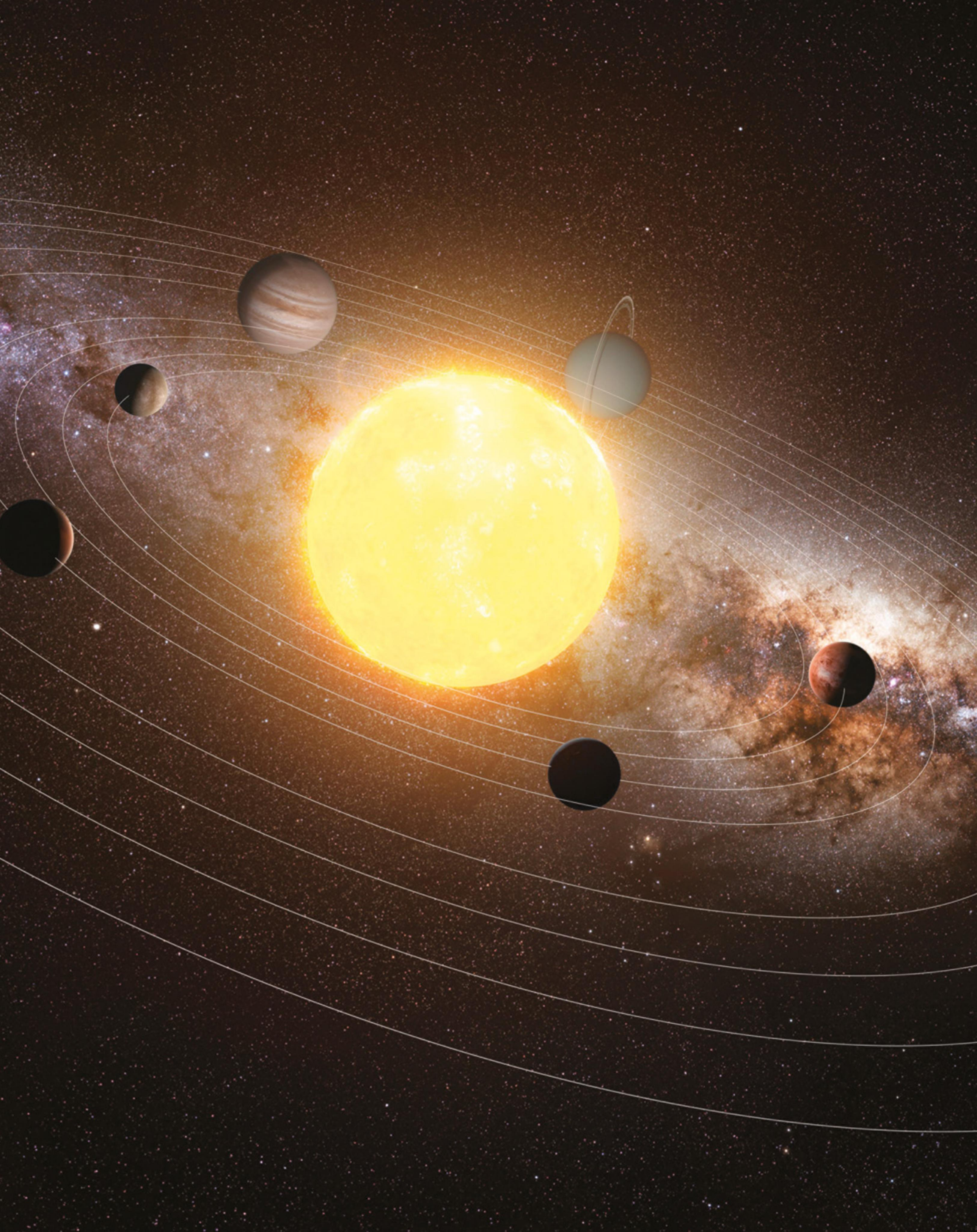
Use the line of best fit to calculate the average acceleration of a block of ice released on an inclined plane with an angle of 45°.

Question 3 (3 marks)

Draw a conclusion that quantifies the acceleration due to gravity for a frictionless surface, including the percentage uncertainty in the value you determine. Show your reasoning.

Question 4 (1 mark)

Calculate the percentage error for your calculated value compared to the theoretical value, $g = 9.8\,m\,s^{-2}$.



CHAPTER

04 Universal gravitation and orbital mechanics

Gravity is the force that drives the universe. It was gravity that first caused atoms to congregate together to form the first nebulas, stars and planets. An understanding of gravity is fundamental to understanding the universe.

This chapter centres on the law of universal gravitation. This will be used to predict the size of the gravitational force experienced by an object and the idea of a gravitational field.

Universal gravitation and uniform circular motion provide the foundation for understanding the motion of celestial bodies such as moons, planets, and galaxies, as well as artificial satellites used in digital technologies. A thorough understanding of these principles leads to the laws of planetary motion, which describe and predict the behaviour of these objects.

Syllabus subject matter

ORBITAL MECHANICS

- Describe the Law of Universal Gravitation. **4.1**
- Solve problems involving the magnitude of the gravitational force between two masses using $F = \frac{GMm}{r^2}$. **4.1**
- Describe the concept of gravitational fields. **4.2**
- Solve problems involving the gravitational field strength at a distance from an object using $g = \frac{F}{m} = \frac{GM}{r^2}$. **4.2**
- State the three laws of planetary motion. **4.3**
- Describe the relationship between the Law of Universal Gravitation and uniform circular motion and recognise this as the third law of planetary motion. **4.3**
- Solve problems involving the third law of planetary motion using $\frac{T_a^2}{r_a^3} = \frac{T_b^2}{r_b^3} = \frac{4\pi^2}{GM}$. **4.3**

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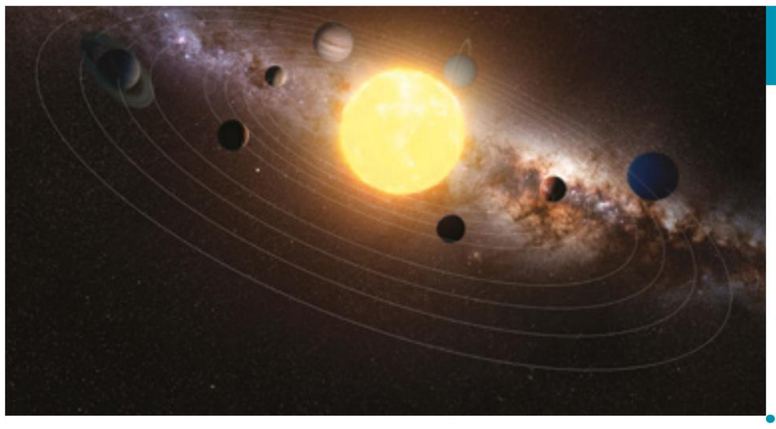
4.1 The law of universal gravitation



BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- recall the law of universal gravitation
- solve problems involving the magnitude of the gravitational force between two masses
- calculate the strength of the gravitational force between two masses
- calculate acceleration due to gravitational force.

Gravity is one of the four fundamental forces in the universe. These fundamental forces will be covered in detail in Chapter 11, the standard model. For now, it is sufficient to understand that the **gravitational force** (gravity) is by far the weakest force of the four. However, because it acts with infinite range and because it is always attractive (unlike electromagnetism which can be attractive or repulsive), gravity is the force that drives the universe.

UNIVERSAL GRAVITATION

The **law of universal gravitation** was introduced in Sir Isaac Newton's book Mathematical Principles of Natural Philosophy (*Principia*) in 1687. This book was described in the Science as a Human Endeavour section in *Pearson Physics Queensland Units 1 & 2*.

The law of universal gravitation states that any two bodies attract each other with a force that is directly proportional to the product of their masses and inversely proportional to the square of the distance between them (See Figure 4.1.1).

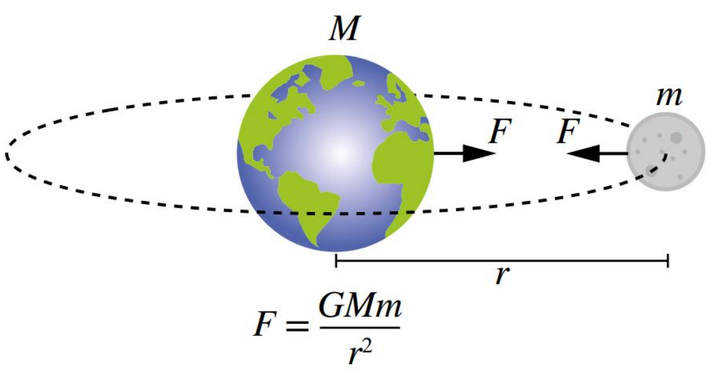


FIGURE 4.1.1 The law of universal gravitation describes the magnitude of the equal-and-opposite forces between two objects, such as the Earth and the Moon.

It is important to recognise the relationship between force and radius as being an example of an **inverse square law**. As r (distance between the centres of the objects) increases, F (gravitational force) decreases dramatically; specifically, a doubling of r will decrease the value of F by a quarter. This is because gravity spreads out in all directions around any object with mass, decreasing in magnitude as it spreads over a larger region.

You will continue to see examples of the inverse square law as you progress through units 3 and 4. Typically, this applies to scenarios involving things which radiate spherically in all directions. For example, you may recall that light behaved according to an inverse square law because it too radiates in all directions (refer to Chapter 11 in *Pearson Physics Queensland Units 1 & 2*). This concept will be explored further in Module 4.2.

Newton used the Moon's orbit to confirm the inverse square law and its role in the law of universal gravitation. He was able to show that the same force which created the Moon's orbit also caused objects to fall here on Earth, such as an apple falling from a tree. He did this by comparing the acceleration experienced by these objects which is explored further in worked example 4.1.1.

Mathematically, the law of universal gravitation is expressed as: $F = \frac{GMm}{r^2}$

where

F is the gravitational force (N)

M is the mass of object 1, typically the larger object (kg)

m is the mass of object 2, typically the smaller object (kg)

r is the distance between the centres of M and m (m)

G is the gravitational constant, 6.67×10^{-11} (N m^2 kg^{-2})

Worked example 4.1.1

IDENTIFYING THE RELATIONSHIP BETWEEN GRAVITATIONAL FORCE AND DISTANCE

Newton used the Moon's orbit to confirm the inverse square law and its role in the law of universal gravitation

For the following questions, treat the orbit of the Moon as a uniform circular motion and refer to the values below.

Moon's orbital period = 2.36×10^6 s

Average radius of the Moon's orbit = 3.84×10^8 m

Earth's radius = 6.37×10^6 m

a Calculate the ratio of the centripetal acceleration experienced by the Moon to the acceleration of a falling apple.

Thinking	Working
Use the uniform circular motion equations (from Chapter 3) to find the centripetal acceleration experienced by the Moon.	$a_c = \frac{v^2}{r}$ and $v = \frac{2\pi r}{T}$ $\therefore a_c = \frac{4\pi^2 r}{T^2}$
Substitute the known values.	$a_c = \frac{4\pi^2 \times 3.84 \times 10^8}{\left(2.36 \times 10^6\right)^2}$ $= 2.72 \times 10^{-3}\,\text{ms}^{-2}$
Calculate the ratio of the centripetal acceleration experienced by the Moon to the acceleration of a falling apple.	$\frac{a_c}{g} = \frac{2.72 \times 10^{-3}}{9.8}$ $\approx \frac{1}{3600}$ The centripetal acceleration of the Moon in orbit is approximately $\frac{1}{3600}$ of the acceleration of the falling apple.

b Calculate the ratio of the radius of the Moon's orbit to the radius of Earth.

Thinking	Working
Calculate the ratio of the radius of Earth to the radius of the Moon's orbit.	$\frac{r_{\text{Earth}\to\text{Moon}}}{r_{\text{Earth}}} = \frac{3.84 \times 10^8}{6.37 \times 10^6}$ ≈ 60 The distance from Earth to the Moon is approximately 60 times greater than the radius of Earth.

c Use the values from **a** and **b** to identify the relationship between force and distance.

Thinking	Working
Consider from part **a** that the acceleration on the Moon is less than the acceleration on the apple, and from part **b** that the Moon is much further from Earth than the apple. This demonstrates the relationship must include an inverse. Considering the values 60 and 3600: $60^2 = 3600$. Or, more appropriately $\frac{1}{3600} = \frac{1}{60^2}$	$\frac{1}{3600} = \frac{1}{60^2}$ $\therefore a_c \propto \frac{1}{r^2}$
Use the second law of motion (refer to *Pearson Physics Queensland Units 1 & 2*) to relate acceleration to force.	$F = ma \therefore F \propto \frac{1}{r^2}$

➤ Try yourself 4.1.1

IDENTIFYING THE RELATIONSHIP BETWEEN GRAVITATIONAL FORCE AND DISTANCE

Apply Newton's calculations as if you were a Martian scientist comparing the acceleration of Mars's small, close-orbiting moon Phobos with the acceleration of a falling Martian apple.

Use 9.38×10^6 m as the radius of the orbit of Phobos, and 7 hours 40 minutes as the period of Phobos's orbit. Use $3.71\,\text{m}\,\text{s}^{-2}$ as the acceleration of a falling apple on the Martian surface and 3.39×10^6 m as the radius of Mars.

a Calculate the ratio of the centripetal acceleration experienced by Phobos to the acceleration of a falling apple.

b Calculate the ratio of the radius of Phobos's orbit to the radius of Mars.

c Use the values from a and b to identify the relationship between force and distance.

GRAVITATIONAL ATTRACTION BETWEEN TWO OBJECTS

Newton was able to verify the proportionality of universal gravitation as being an inverse square law but was unable to establish the value of the proportionality constant. In the law of universal gravitation, the proportionality constant is called the **gravitational constant** G and is equal to $6.67 \times 10^{-11}\,(\text{N}\,\text{m}^2\,\text{kg}^{-2})$. Newton was unable to establish the value of G because Earth's mass was unknown at the time. The best he could do was to calculate the value of the product $G \times M_{\text{Earth}}$.

This equation only considers Earth's mass. This is because for most everyday objects, such as Newton's apple, both their mass and their gravitational force are negligible, as they are several orders of magnitude smaller than those of Earth. Worked example 4.1.2 demonstrates this, showing the force between two adult humans is of the order of a millionth of a newton. To give an idea of scale, that is about one ten-thousandth the weight of a feather.

Worked example 4.1.2

GRAVITATIONAL ATTRACTION BETWEEN SMALL OBJECTS

Mark has a mass of 90.0 kg and his dance partner Bec has a mass of 75.0 kg. The distance between their centres is 85.0 cm. Calculate the magnitude of the force of gravitational attraction between the dancers.

Thinking	Working
Recall the equation for the law of universal gravitation.	$F = \dfrac{GMm}{r^2}$
Identify the information required and convert values into appropriate units where necessary.	$G = 6.67 \times 10^{-11}\,\text{N}\,\text{m}^2\,\text{kg}^{-2}$ $M = 90.0\,\text{kg}$ $m = 75.0\,\text{kg}$ $r = 85.0\,\text{cm} = 0.85\,\text{m}$
Substitute the values into the equation.	$F = \dfrac{(6.67 \times 10^{-11}) \times 90 \times 75}{0.85^2}$
Solve the equation.	$F = 6.2 \times 10^{-7}\,\text{N}$

➤ Try yourself 4.1.2

GRAVITATIONAL ATTRACTION BETWEEN SMALL OBJECTS

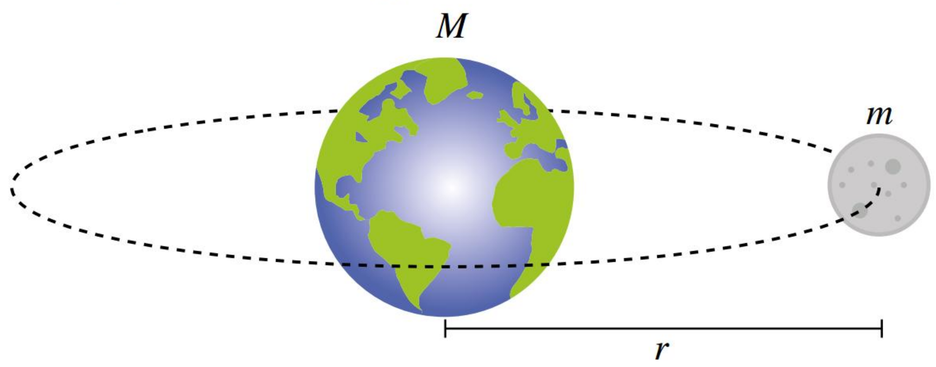
In an experiment to verify gravitational attraction (Henry Cavendish, 1798), a large lead mass was suspended beside a smaller mass so that the centres of the two balls were 23 mm apart. Ball 1 had a mass of 160 kg and ball 2 had a mass of 0.73 kg. Calculate the magnitude of the force of gravitational attraction between them.

Gravitational forces between everyday objects are so small (as seen in worked example 4.1.2) that forces are hard to detect without specialised equipment. When solving problems such as these, it is common practice to ignore the smaller objects in the calculation. For the gravitational force to become significant, at least one of the objects must have a very large mass, such as a planet.

Worked example 4.1.3

GRAVITATIONAL ATTRACTION BETWEEN MASSIVE OBJECTS

Calculate the magnitude of the force of gravitational attraction between the Moon and Earth given the average radius of the Moon's orbit is 3.84×10^8 m.



Thinking	Working
Recall the equation for the law of universal gravitation.	$F = \frac{GMm}{r^2}$
Identify the information required. The mass of the Moon and Earth are in the QCAA Formula and data book. $m_{Moon} = 7.35 \times 10^{22}$ kg $m_{Earth} = 5.97 \times 10^{24}$ kg	$G = 6.67 \times 10^{-11}$ N m^2 kg^{-2} $M = 5.97 \times 10^{24}$ kg $m = 7.35 \times 10^{22}$ kg $r = 3.84 \times 10^8$ m
Substitute the values into the equation.	$F = \frac{(6.67 \times 10^{-11}) \times (5.97 \times 10^{24}) \times (7.35 \times 10^{22})}{(3.84 \times 10^8)^2}$
Solve the equation.	$F = 1.98 \times 10^{20}$ N

➤ Try yourself 4.1.3

GRAVITATIONAL ATTRACTION BETWEEN MASSIVE OBJECTS

Calculate the magnitude of the force of gravitational attraction between Earth and the Sun given the average radius of Earth's orbit is 1.50×10^{11} m.

The forces in Worked example 4.1.3 are trillions and trillions of times greater than those in Worked example 4.1.2. This illustrates just how negligible the gravitational force is from everyday objects compared to planetary bodies, and why everyday objects can be ignored in these calculations without impacting accuracy.

EFFECT OF GRAVITY

Recall that according to the third law of motion, all forces occur in equal-and-opposite pairs. An example of such a pair is shown in Figure 4.1.2. Earth exerts a gravitational force on the Moon and, conversely, the Moon exerts an equal and opposite force on Earth.

Using the *second* law of motion ($F_{net} = ma$), you can determine that the equal gravitational force between the two bodies results in a much smaller acceleration of Earth than of the Moon.

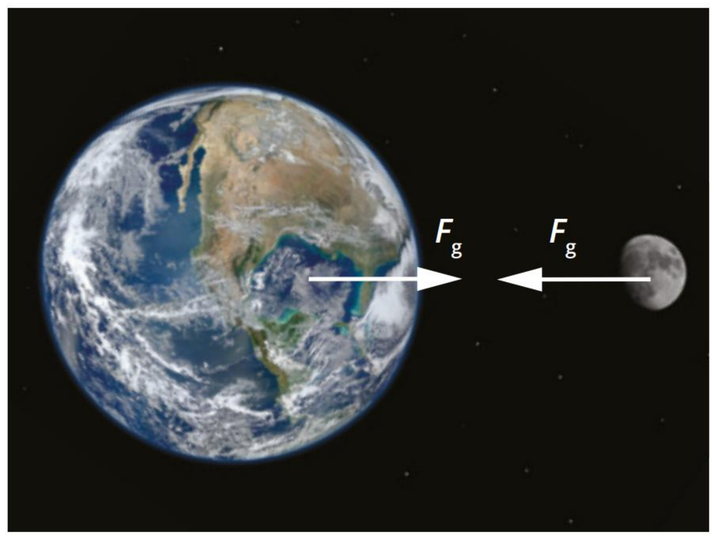


FIGURE 4.1.2 Earth and the Moon exert gravitational forces on each other.

Worked example 4.1.4

ACCELERATION CAUSED BY A GRAVITATIONAL FORCE

The force of gravitational attraction between the Moon and Earth is 1.98×10^{20} N.

Calculate how many times greater the acceleration of the Moon by Earth is than the acceleration of Earth by the Moon.

Thinking	Working
Recall the equation for the second law of motion.	$a = \frac{F_{net}}{m}$
Substitute values into this equation to find the accelerations of the Moon and of Earth. The mass of the Moon and Earth are located in the QCAA Formula and data book. $m_{Moon} = 7.35 \times 10^{22}$ kg $m_{Earth} = 5.97 \times 10^{24}$ kg	$a_{Moon} = \frac{1.98 \times 10^{20}}{7.35 \times 10^{22}} = 2.70 \times 10^{-3}\,\text{m s}^{-2}$ towards Earth. $a_{Earth} = \frac{1.98 \times 10^{20}}{5.97 \times 10^{24}} = 3.32 \times 10^{-5}\,\text{m s}^{-2}$ towards the Moon.
Divide the acceleration of the Moon by the acceleration of Earth to find how many times greater it is.	$\frac{a_{Moon}}{a_{Earth}} = \frac{2.70 \times 10^{-3}}{3.32 \times 10^{-5}} = 81.2$ That is, the acceleration of the Moon due to Earth is approximately 80 times greater than the acceleration of Earth due to the Moon.

➤ Try yourself 4.1.4

ACCELERATION CAUSED BY A GRAVITATIONAL FORCE

The force of gravitational attraction between Earth and a 500.0 g rugby ball kicked into the air is 4.90 N.

Calculate how many times larger the acceleration of the ball is than the acceleration of Earth.

Accelerations caused by gravitational forces between astronomical bodies, as calculated in Worked example 4.1.3, created the motion of the solar system. In the Earth–Moon system, the acceleration of the Moon is many times greater than that of Earth (as shown in worked example 4.1.4), which is why the Moon orbits Earth. Although the Moon's gravitational force causes a much smaller acceleration of Earth, it does have other significant effects, such as the tides. Similarly, Earth and other planets orbit the Sun because their masses are much smaller than the Sun's mass. However, the combined gravitational effect of the planets of the solar system (and Jupiter in particular) causes the Sun to wobble slightly as the planets orbit it.

WEIGHT AND GRAVITATIONAL FORCE

You will have seen previously (Chapter 7 in *Pearson Physics Queensland Units 1 & 2* and Chapter 2 in this book) that the weight of an object is calculated using the formula $F_g = mg$. 'Weight' is simply another name for the gravitational force acting on an object near Earth's surface.

Worked example 4.1.5 shows that the formula for weight $F_g = mg$ and the law of universal gravitation $F = \frac{GMm}{r^2}$ give the same answer for the gravitational force acting on objects on Earth's surface. It is important to note that the distance used in these calculations is the distance between the centres of the two objects, which is effectively the radius of Earth.

ℹ Weight is the force due to gravity.

Mass is the amount of material contained in a body.

In distant space, far from any large body, your weight would be zero, but your mass would be the same as here on Earth (and so, for example, your inertia would be the same, if you were trying to change direction in space).

Worked example 4.1.5

GRAVITATIONAL FORCE AND WEIGHT

Compare the weight of a 30.0 kg child, calculated using $F_g = mg$, with the gravitational force on the child due to Earth, calculated using $F = \frac{GMm}{r^2}$.
Use $r_{Earth} = 6.37 \times 10^6$ m

Thinking	Working
Apply the weight equation. $g = 9.8\,\text{m s}^{-2}$	$F_g = mg$ $= 30.0 \times 9.8$ $= 294\,\text{N}$
Apply the law of universal gravitation with the following values from the QCAA Formula and data book $G = 6.67 \times 10^{-11}\,\text{N m}^2\,\text{kg}^{-2}$ $M_{Earth} = 5.97 \times 10^{24}$ kg	$F = \frac{GMm}{r^2}$ $= \frac{(6.67\times10^{-11})\times(5.97\times10^{24})\times30.0}{(6.37\times10^6)^2}$ $= 6.67\times10^{-11}\times\frac{(5.97\times10^{24})\times30.0}{(6.37\times10^6)^2}$ $= 294\,\text{N}$
Compare the two values.	Both equations give the same result (to within 2 or 3 significant figures).

➤ Try yourself 4.1.5

GRAVITATIONAL FORCE AND WEIGHT

Compare the weight of a 5.0 kg mass on Earth's surface calculated using the formulas $F_g = mg$ and $F = \frac{GMm}{r^2}$. Use $r_{Earth} = 6.37 \times 10^6$ m.

The link between $F_g = mg$ and the law of universal gravitation $F = \frac{GMm}{r^2}$ can also be demonstrated by calculating the acceleration due to gravity at Earth's surface, g. The first step of this process is to combine these two equations.

$$F_g = mg \text{ and } F = \frac{GMm}{r^2}$$

$$\therefore\ mg = \frac{GMm}{r^2}$$

$$g = \frac{GM_{Earth}}{r^2_{Earth}}$$

$$= \frac{(6.67\times10^{-11})\times(5.97\times10^{24})}{(6.37\times10^6)^2}$$

$$\approx 9.8\,\text{m s}^{-2}$$

This calculation shows that the acceleration of objects near the surface of Earth, g, is a result of Earth's mass and radius. If an object is above Earth's surface, the value of r will be greater and therefore the acceleration due to gravity will be smaller, following the inverse square law. This is why the strength of Earth's gravity reduces as you travel away from Earth.

4.1 Review

SUMMARY

- All objects with mass attract one another with a gravitational force.
- The gravitational force acts equally on each of the masses.
- The magnitude of the gravitational force is given by the law of universal gravitation: $F = \frac{GMm}{r^2}$.
- Gravitational forces are usually negligible unless one of the objects is massive, such as a planet.
- The weight of an object on Earth's surface is due to the gravitational attraction of Earth.
- The gravitational field strength at a distance from an object can be found using: $g = \frac{F}{m} = \frac{GM}{r^2}$.

KEY QUESTIONS

Describe

1 The law of universal gravitation states $F = \frac{GMm}{r^2}$.

a Identify the relationship between force and mass.

b Identify the relationship between force and radius.

2 State what the symbol r represents in the law of universal gravitation.

3 Contrast weight with mass.

4 Describe the properties of an inverse square law.

Apply

5 Determine what happens to the gravitational force acting between two masses m_1 and m_2 a distance r apart, in each of the following situations.

a The mass of m_1 is doubled.

b The distance r is doubled.

c The distance r is quadrupled.

6 Explain why the acceleration of the Moon caused by the gravitational force of Earth is much larger than the acceleration of Earth due to the gravitational force of the Moon.

7 A 5 kg ball and a 0.5 kg ball are dropped from a height. With reference to gravitational force and gravitational acceleration and ignoring drag effects, describe the order the balls collide with the ground.

Analyse

8 Calculate the weight of Aphrodite, a 75.0 kg astronaut standing on the surface of Venus, given that the planet has a mass of 4.87×10^{24} kg and a radius of 6050 km.

9 Consider gravitational attraction between the Sun and Mars, given that the mass of the Sun is 1.99×10^{30} kg, the mass of Mars is 6.39×10^{23} kg and the average distance between the two centres of mass is 2.28×10^{11} m.

a Calculate the gravitational attraction between the Sun and Mars.

b Calculate the acceleration of Mars towards the Sun.

10 On 14 April 2014, Mars came within 93 000 000 km of Earth. At that point its gravitational effect on Earth was the strongest it had been for over 6 years. Use $m_{Mars} = 6.39 \times 10^{23}$ kg to answer the questions below.

a Calculate the magnitude of the gravitational force between Earth and Mars on 14 April 2014.

b Calculate the force of the Sun on Earth, given that the distance between them is 150 000 000 km.

c Contrast your answers to parts **a** and **b** by expressing the Mars–Earth force as a percentage of the Sun–Earth force.

d Calculate the distance r between Earth and Mars at the greatest distance between the two planets, where the gravitational force between Mars and Earth is 5.03×10^{15} N.

11 Two astronauts, Sandra and George, each of mass 150 kg (including their suits), float in outer space 1.00 m apart.

a Calculate the gravitational force between them.

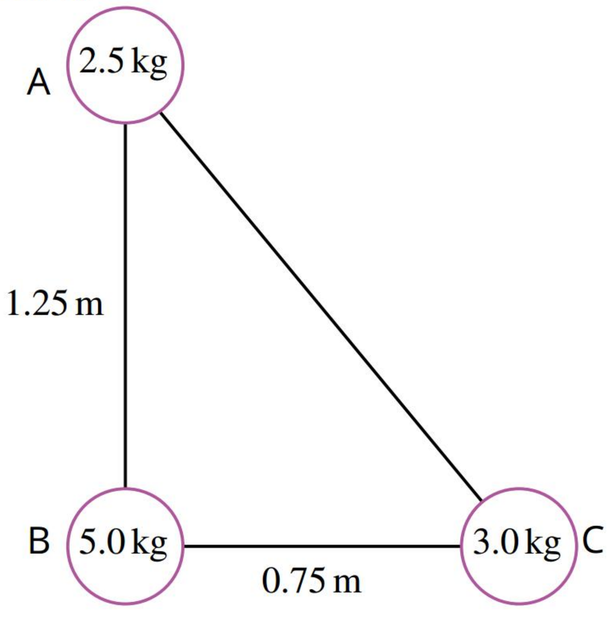
b Calculate the resulting acceleration of each astronaut.

12 Newton's work on universal gravitation allowed astronomers to predict the existence of Neptune in 1864, the eighth planet in the solar system, based on variations in the orbit of Uranus.

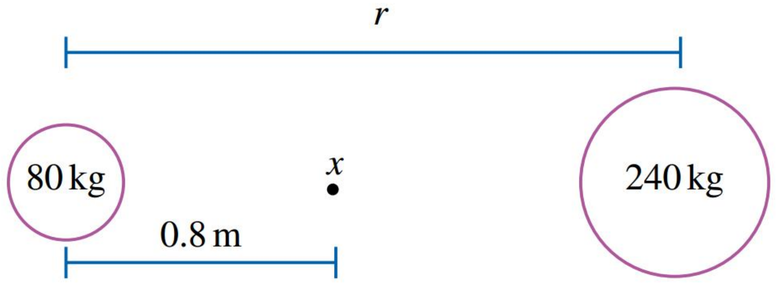
a Calculate the maximum force between the two planets if the mass of Uranus is 8.68×10^{25} kg, the mass of Neptune is 1.02×10^{26} kg, and the shortest distance between the two planets is 1.63×10^{9} km.

b Contrast this with the gravitational force of the Sun on Uranus if the mass of the Sun is 1.99×10^{30} kg and the distance from the Sun to Uranus is 2.87×10^{9} km.

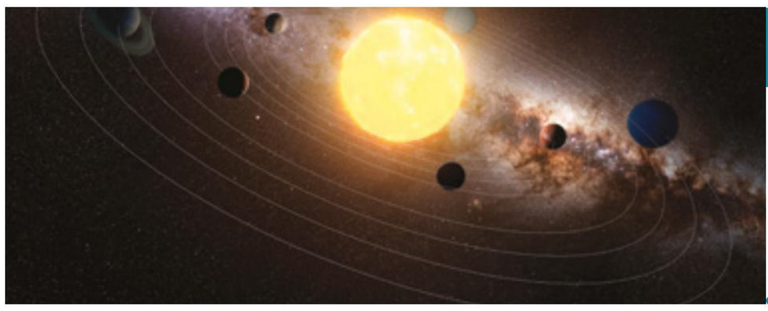
13 Three masses A, B and C are arranged as per the diagram shown below. Calculate the gravitational force on A.



14 Two asteroids are floating through the asteroid belt close to each other as shown in the diagram below. The larger asteroid has a mass of 240 kg, the smaller asteroid a mass of 80 kg. It is known the point of zero net force (x) is 0.8 m from the smaller asteroid. Determine the distance between the two asteroids (r).



4.2 Gravitational fields



BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- describe gravitational fields
- solve problems involving the gravitational field strength at a distance from an object.

The law of universal gravitation describes the force acting between two mutually attracting bodies. In reality, complex systems like the solar system involve several objects—such as the Sun and planets (Figure 4.2.1)—that are all exerting attractive forces on each other at the same time.

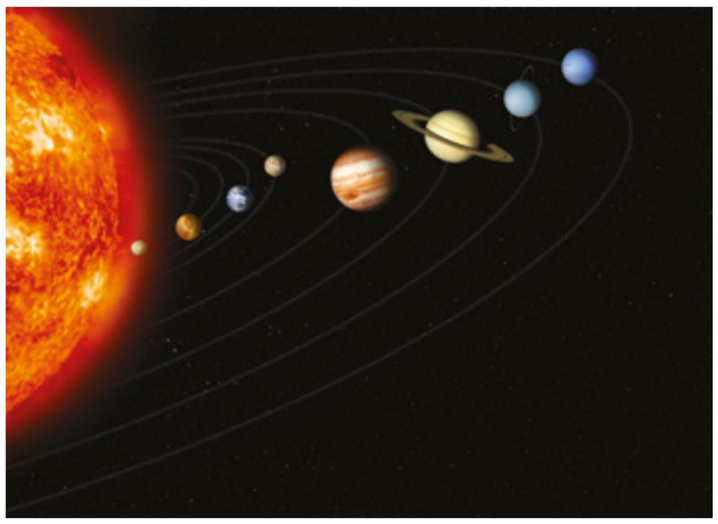


FIGURE 4.2.1 The solar system is a complex gravitational system.

In the 18th century, to simplify the process of calculating the effect of simultaneous gravitational forces, a model was developed known as the gravitational field. In the following centuries, the idea of a **field** was also applied to other forces and has become a very important concept in physics.

A **gravitational field** is a region in which a gravitational force is exerted on all matter within that region. Every physical object has an accompanying gravitational field. For example, the space around your body contains a gravitational field because any other object that comes into this region will experience a (small) force of gravitational attraction to your body.

The gravitational field around a large object such as a planet is much more significant than that around a small object. Earth's gravitational field exerts a significant influence on objects on its surface and even thousands of kilometres into space.

REPRESENTING GRAVITATIONAL FIELDS

Over time, scientists have developed a commonly understood method of representing fields using a series of arrows known as field lines (Figure 4.2.2). For gravitational fields, these can be interpreted as follows.

- The direction of the arrowhead indicates the direction of the gravitational force.
- The space between the arrows indicates the relative magnitude of the field:
  - closely spaced arrows indicate a strong field
  - widely spaced arrows indicate a weaker field.
- Parallel field lines indicate constant or uniform field strength.
- Gravitational field lines emanate from the source of the field.
- The lines never cross.

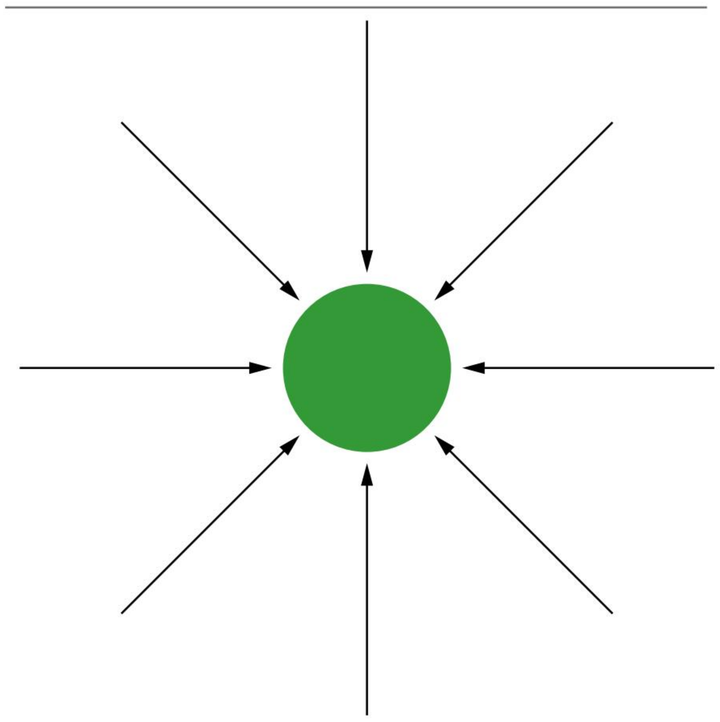


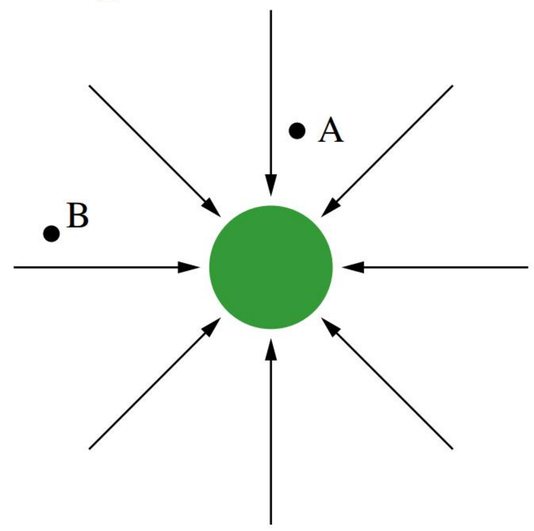
FIGURE 4.2.2 The arrows in this gravitational field diagram indicate that objects will be attracted towards the mass in the centre. The spacing of the lines shows that force will be strongest at the surface of the central mass and weaker further away from it.

In theory, an infinite number of field lines could be shown, but in fact only a few are needed to represent the behaviour of the field. The size of the gravitational force acting on a mass in the region of a gravitational field is determined by the strength of the field, and the force acts in the direction of the field.

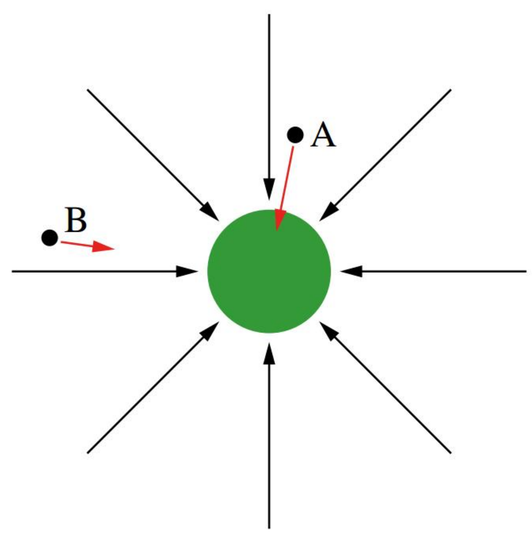
Worked example 4.2.1

INTERPRETING GRAVITATIONAL FIELD DIAGRAMS

The diagram below shows the gravitational field of a moon.



a Use arrows to indicate the direction of the gravitational force acting at points A and B.

Thinking	Working
The direction of the field arrows indicates the direction of the gravitational force, which is inwards towards the centre of the moon.	

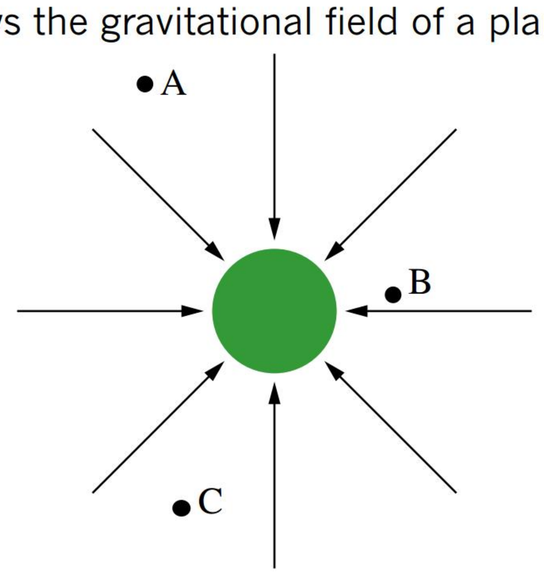
b Describe the relative strength of the gravitational field at each point.

Thinking	Working
The closer the field lines, the stronger the force. The field lines are closer together at point A than they are at point B, as point A is closer to the moon.	The field is stronger at point A than at point B.

➤ Try yourself 4.2.1

INTERPRETING GRAVITATIONAL FIELD DIAGRAMS

The diagram below shows the gravitational field of a planet.



a Use arrows to indicate the direction of the gravitational force acting at points A, B and C.

b Describe the relative strength of the gravitational field at each point.

For Earth's gravitational field (Figure 4.2.3a), it is clear that the gravitational field is directed towards Earth and increases in strength as Earth is approached. However, in everyday situations where Earth's surface can be approximated as if it were a flat surface, then the gravitational field lines are approximately parallel, indicating a uniform field (Figure 4.2.3b).

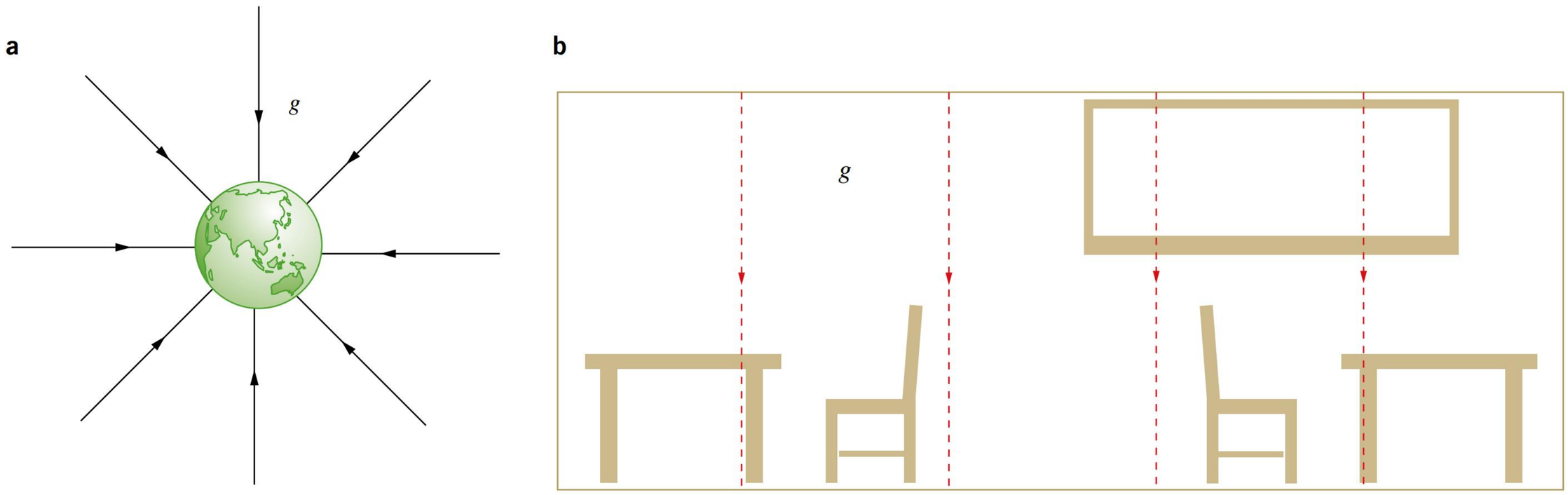


FIGURE 4.2.3 (a) On a large-scale Earth's gravitational field is represented by radial field lines pointing towards the centre of Earth. (b) on a small-scale Earth's gravitation field is represented by evenly spaced parallel lines pointing towards Earth's surface.

GRAVITATIONAL FIELD STRENGTH

In Module 4.1, the acceleration due to gravity of objects near Earth's surface was calculated. The first step of this was the combination of the equations $F_g = mg$ and $F = \frac{GMm}{r^2}$ which yields:

$$g = \frac{F}{m} = \frac{GM}{r^2}$$

This is a noteworthy relationship as it allows for the calculation of the acceleration due to gravity at a distance from an object, given its mass.

The value g is also used as a measure of **gravitational field strength**, in which case it is written with the equivalent units of $\mathrm{N\,kg^{-1}}$ rather than $\mathrm{m\,s^{-2}}$. This means $g_{\mathrm{Earth}} = 9.8\,\mathrm{N\,kg^{-1}}$. These units indicate that objects on Earth's surface experience 9.8 N of gravitational force for every kilogram of their mass.

$g = \frac{F}{m}$

where

g is gravitational field strength ($\mathrm{N\,kg^{-1}}$)

F is the force due to gravity (N)

m is the mass of an object in the field (kg)

Worked example 4.2.2

CALCULATING GRAVITATIONAL FIELD STRENGTH

When Maree hangs a 1.00 kg mass from a spring balance, the balance measures a downwards force of 9.8 N.

Calculate the gravitational field strength of Earth at this location, according to this experiment.

Thinking	Working
Recall the equation for gravitational field strength.	$g = \frac{F}{m}$
Substitute in the appropriate values.	$g = \frac{9.8}{1.00}$
Solve the equation.	$g = 9.8\,\mathrm{N\,kg^{-1}}$ downwards

The gravitational field strength at a distance from an object can be found using $g = \frac{GM}{r^2}$

where

g is the gravitational field strength ($\mathrm{N\,kg^{-1}}$)

G is the gravitational constant, $6.67 \times 10^{-11}\,\mathrm{N\,m^2\,kg^{-2}}$

M is the mass of the planet or moon (the central body) (kg)

r is the radius of the planet or moon (m)

➤ Try yourself 4.2.2

CALCULATING GRAVITATIONAL FIELD STRENGTH

Dion uses a spring balance to measure the weight of a piece of wood as 2.53 N. If the piece of wood has a mass of 259 g, calculate the gravitational field strength indicated by this experiment.

The inverse square law

In theory, gravitational fields extend infinitely out into space. However, since the magnitude of the gravitational force decreases with distance according to the inverse square law, eventually these fields become negligibly weak.

The concept of a field is a very powerful tool for understanding forces that act at a distance. It has also been applied to such forces as the electrostatic force between charged objects and the force between two magnets.

The study of gravitational fields introduces the concept of the inverse square law. From the point source of a field, whether it be gravitational or electric, the field will spread out radially in three dimensions. When the distance from the source is doubled, the field will be spread over four times the original area.

Figure 4.2.4 shows an increasing distance from the field source of r then $2r$ then $3r$. As you can see, a projection of one square at distance r increases to four squares (2^2) at distance $2r$ and increases to nine squares (3^2) at distance $3r$.

As the 'inverse' part of the inverse square law implies, at a distance $2r$ from the source the strength of the field will be reduced to a quarter of the field at distance r. The force the field would exert at that distance will also be reduced to a quarter. At a distance $3r$ from the source, the field will be reduced to one-ninth of the field at distance r, and so on. (Refer to the SkillBuilder on page 456 of *Pearson Physics Queensland Units 1 & 2* for more information on proportional reasoning.)

The gravitational field strength at different altitudes can be calculated by adding the **altitude** (height above the surface of Earth) to the radius of Earth to calculate the distance the object is from Earth's centre (Figure 4.2.5).

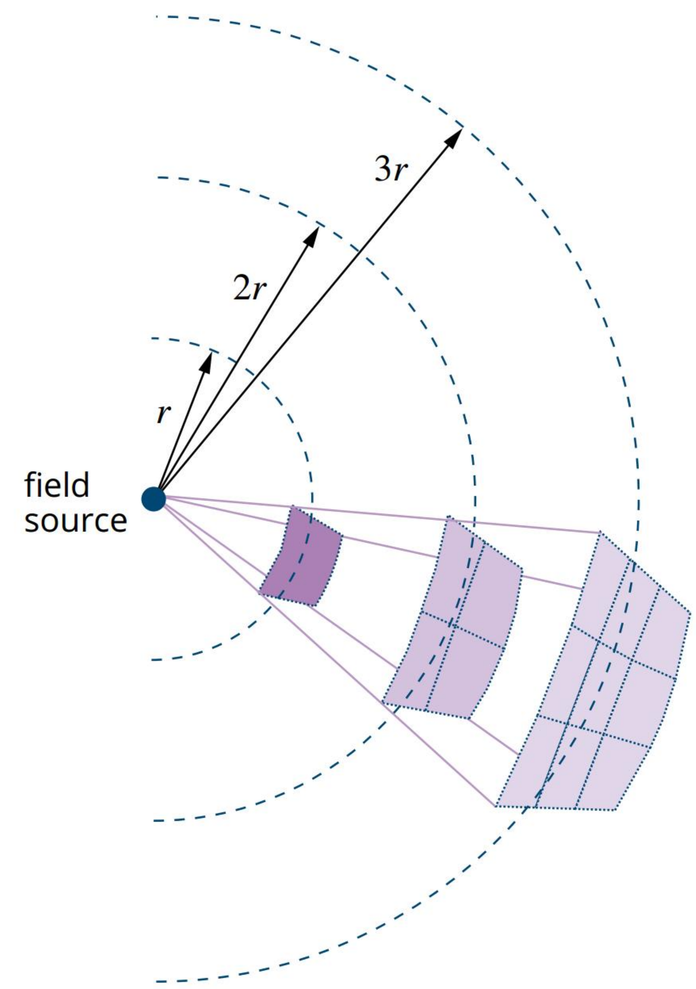


FIGURE 4.2.4 As the distance from the source of a field increases, the field is spread over an area that increases with the square of the distance from the source. This means that the strength of the field decreases by the same ratio.

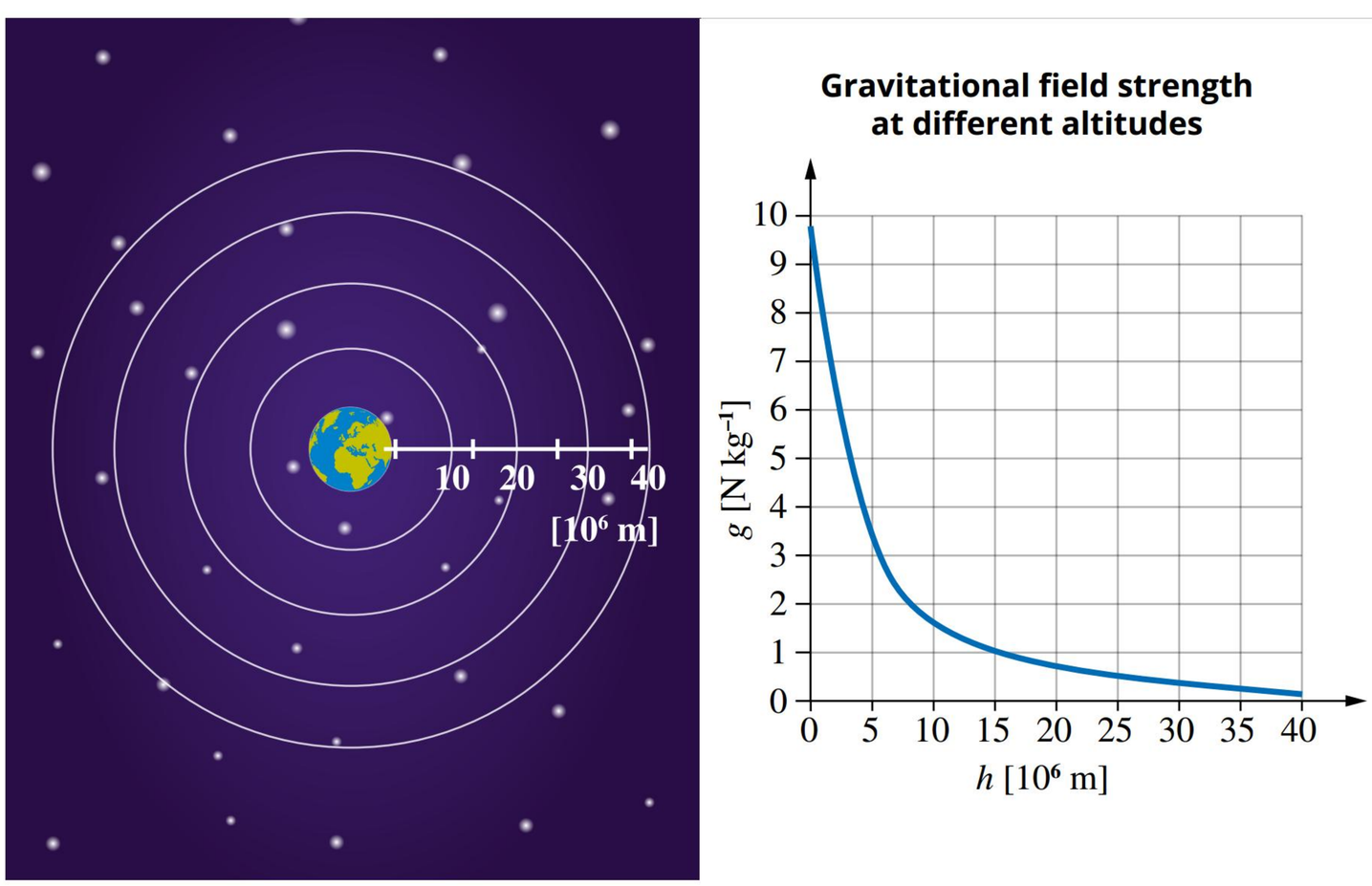


FIGURE 4.2.5 As the height above the surface of Earth (h) increases from 0 to 40×10^6 m, the value for g decreases rapidly from 9.8 N kg^{-1}, according to the inverse square law.

Gravitational field strength varies with distance according to the inverse square law:

$$g \propto \frac{1}{r^2}$$

where

g is gravitational field strength (N kg^{-1})

r is the distance from the source of the gravitational field (m).

Worked example 4.2.3

CALCULATING GRAVITATIONAL FIELD STRENGTH AT DIFFERENT ALTITUDES

Contrast the magnitude of Earth's gravitational field at the top of Mt Everest (8848 m) with the mean gravitational field strength at sea level, $9.8\,\text{N kg}^{-1}$ by calculating the percentage difference.

$r_{\text{Earth}} = 6.37 \times 10^6\,\text{m}$

Thinking	Working
Recall the formula for gravitational field strength.	$g = \frac{GM}{r^2}$
Add the height of Mt Everest to the radius of Earth.	$r = 6.37 \times 10^6 + 8848\,\text{m}$ $= 6.379 \times 10^6\,\text{m}$
Substitute the values into the formula.	$= \frac{(6.67 \times 10^{-11}) \times (5.97 \times 10^{24})}{(6.379 \times 10^6)^2}$ $= 9.79\,\text{N kg}^{-1}$
Calculate the percentage difference.	$\frac{9.8 - 9.79}{9.8} \times 100\%$ $= 0.10\%$ The gravitational field strength at the top of Mt Everest is only 0.10% less than the mean value at sea level.

➤ Try yourself 4.2.3

CALCULATING GRAVITATIONAL FIELD STRENGTH AT DIFFERENT ALTITUDES

The International Space Station (ISS) orbits at an altitude of approximately 400 km.

Contrast the magnitude of the gravitational field strength at this height with the mean gravitational field strength at sea level, $9.8\,\text{N kg}^{-1}$ by calculating the percentage difference.

$r_{\text{Earth}} = 6.37 \times 10^6\,\text{m}$

FIGURE 4.2.6 The gravitational field strength on the surface of Mars (shown here) is different from the gravitational field strength on the surface of Earth, which, in turn, is different from that on the Moon. This is because each planet possesses a unique mass and radius.

Gravitational field strengths on another planet or moon

The gravitational field strength on the surface of the Moon is $1.62\,\text{N kg}^{-1}$, which is much less than on Earth. To explain this, the following relationship is required.

$$g = \frac{F}{m} = \frac{GM}{r^2}$$

This relationship explains why different planets have differing values of gravity – different planets have different masses and radii, and therefore a different value for g. This relationship can be used to calculate the gravitational field strength on the surface of any astronomical object, such as Mars (Figure 4.2.6).

Worked example 4.2.4

GRAVITATIONAL FIELD STRENGTH ON ANOTHER PLANET OR MOON

Calculate the magnitude of the gravitational field on the surface of the Moon, given its radius is 1740 km.	
Thinking	**Working**
Recall the formula for gravitational field strength.	$g = \frac{GM}{r^2}$
Convert the Moon's radius to metres.	$r = 1740\,\text{km}$ $= 1740 \times 1000\,\text{m}$ $= 1.74 \times 10^6\,\text{m}$
Substitute values into the formula. The mass of the Moon is located in the QCAA Formula and data book. $m_{\text{Moon}} = 7.35 \times 10^{22}$ kg	$= \frac{6.67 \times 10^{-11} \times 7.35 \times 10^{22}}{\left(1.74 \times 10^6\right)^2}$ $= 1.62\,\text{N kg}^{-1}$

➤ Try yourself 4.2.4

GRAVITATIONAL FIELD STRENGTH ON ANOTHER PLANET OR MOON

Calculate the strength of the gravitational field on the surface of the distant exoplanet Kepler-10C, the largest known rocky planet, which is 17 times more massive than Earth.

$M_{\text{Kepler–10C}} = 1.0 \times 10^{26}\,\text{kg}$

$r_{\text{Kepler–10C}} = 15\,000\,\text{km}$

4.2 Review

SUMMARY

- A gravitational field is a region in which a gravitational force is exerted on all matter within that region.
- A gravitational field can be represented by a gravitational field diagram.
  - The arrowheads indicate the direction of the gravitational force.
  - The spacing of the lines indicates the relative strength of the field. The closer the line spacing, the stronger the field.
- The strength of a gravitational field can be calculated using:

$$g = \frac{F}{m} = \frac{GM}{r^2}$$

- The gravitational field strength on the surface of any other planet depends on the mass and radius of the planet.
- To calculate gravitational field strength above the surface of a planet the radius and height must be combined.
- The gravitational field strength on Earth's surface is approximately $9.8\,\text{N}\,\text{kg}^{-1}$.

KEY QUESTIONS

Describe

1 State the units used to express acceleration due to gravity. State the average value for the acceleration due to gravity at Earth's surface.

2 Compare the units for gravitational acceleration with the units for gravitational field strength.

Apply

3 Describe the direction in which gravitational field lines point within a classroom at Earth's surface. Explain why the field lines are assumed to be parallel.

4 Explain what distance would be used to determine the gravitational acceleration at a specified height above Earth's surface.

Analyse

5 Contrast the magnitude of the gravitational field at a distance of 1200 km from the centre of a planet with that at a distance of 400 km.

6 Determine the gravitational field strength in the classroom of Imogen and Scott who use a spring balance to measure the weight of a 149 g set of slotted masses to be 1.45 N.

7 Calculate the magnitude of Earth's gravitational field for each different type of orbit listed in the table below.

$r_{\text{Earth}} = 6370\,\text{km}$

$M_{\text{Earth}} = 5.97 \times 10^{24}\,\text{kg}$

	Type of orbit	Altitude (km)
a	low-Earth orbit	2000.0
b	medium-Earth orbit	10 000.0
c	semi-synchronous orbit	20 200.0
d	geosynchronous orbit	35 786.0

8 On 12 November 2014, after many attempts, the Rosetta spacecraft landed a probe on the comet 67P/Churyumov–Gerasimenko.

a Calculate the magnitude of the comet's gravitational field strength at its surface, assuming this comet is a roughly spherical object with a mass of $9.98 \times 10^{12}\,\text{kg}$ and a diameter of 1.80 km.

b Compare this gravitational field strength with that at Earth's surface, $9.8\,\text{m}\,\text{s}^{-2}$.

9 When a large star uses up its fuel and goes supernova, its atomic structure may collapse to form a very small, very dense body known as a neutron star. A typical neutron star may still have a mass larger than the Sun, but the size of a small city.

a Compare the gravitational field strength on the surface of such a star with that of the Sun.

b Calculate the gravitational field strength at the surface of a neutron star that has mass $3 \times 10^{30}\,\text{kg}$ and radius 10 km.

c Compare this to the strength of the gravitational field at Earth's surface.

d Calculate the distance from the neutron star where the gravitational field strength is the same as the gravitational field strength at the surface of Earth. Use $g_{\text{Earth}} = 9.8\,\text{m}\,\text{s}^{-2}$.

10 A hypothetical planet in a distant solar system is distinctly non-spherical in shape. Its polar radius ($5.0 \times 10^3\,\text{km}$) is only half of its equatorial radius ($1.00 \times 10^4\,\text{km}$).

a Describe how different the gravitational field strength would be at the equator compared to the poles.

b Calculate the magnitude of the field at the equator, and confirm your answer from part **a**. The gravitational field strength at the poles is $8.10\,\text{N}\,\text{kg}^{-1}$.

11 Calculate the distance, in Earth radii, of an astronaut from the centre of Earth when the astronaut travels away from Earth to a region in space where the gravitational force due to Earth is only 1.0% of that at Earth's surface.

12 Consider the force of gravity on Mercury, a small rocky planet.

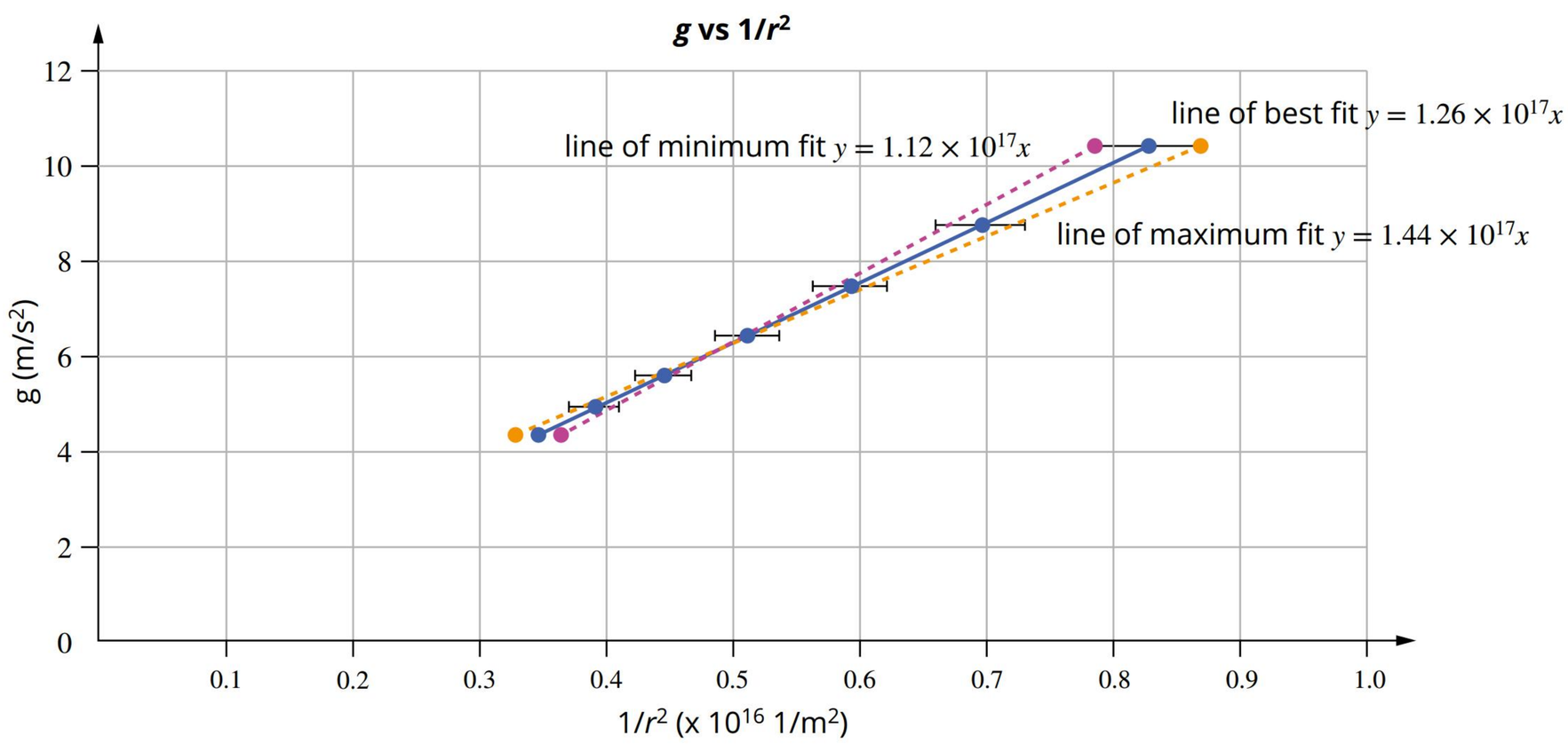
- **a** Explain the effect the much smaller radius of Mercury has on gravitational acceleration. Mercury has a radius only a third of the radius of Earth.
- **b** Explain the effect the much smaller mass has on gravitational acceleration. The mass of Mercury is much smaller than that of Earth.
- **c** Calculate gravitational acceleration on the surface of Mercury, given that Mercury has a mass of 3.29×10^{23} kg and a radius of 2440 km.
- **d** Calculate the weight of Hermes, a 75.0 kg astronaut standing on the surface of Mercury.

13 Oberon, the largest moon of Uranus, has a radius of 761.4 km and a mean gravitational acceleration of $0.358\,\text{ms}^{-2}$. Calculate the mass of Oberon.

The following information relates to question **14-15**

A probe is launched into the atmosphere of a planet which is known to be a gas giant. The probe records the gravitational acceleration it experiences as well as a measure of its distance from the centre of the gas giant. The researchers have processed and plotted this data on the graph below.

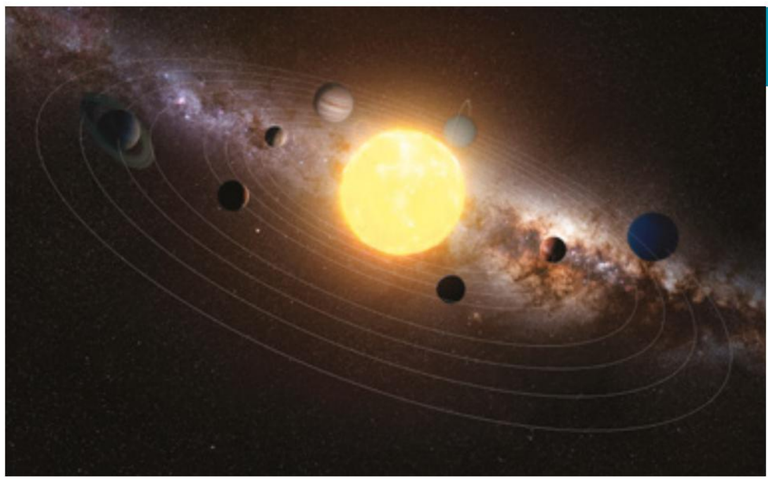
Note: the *y*-intercept is negligible and has been removed from the data and the *y*-axis error bars are too small to be visible.



14 Identify the mathematical relationship between gravitational acceleration and distance, including the uncertainty of the gradient.

15 Draw a conclusion from the mathematical relationship which quantifies the mass of the gas giant. Include the absolute uncertainty in this value.

4.3 Laws of planetary motion



BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- recall the three laws of planetary motion
- describe the relationship between the Law of Universal Gravitation and uniform circular motion
- recognise the third law of planetary motion as a relationship between the Law of Universal Gravitation and uniform circular motion
- use the third law of planetary motion to calculate the radii and period of planets and satellites.

FIGURE 4.3.1 Johannes Kepler was the first to work out that the planets do not travel in circular paths, but rather in elliptical paths.

Kepler, a German astronomer (Figure 4.3.1), published his three laws regarding the motion of planets in 1609. This was about 80 years before Newton published the law of universal gravitation. Kepler used extensive observations collected by Tycho Brahe to formulate his laws, which can be regarded as empirical as they had no immediate basis in theory. These laws related to the motion of the planets in orbit around the Sun, but these laws can be used for any **satellite** in orbit around any central mass. Kepler's essential contribution was the introduction of elliptical orbits, which were able to explain the motion of planets more accurately than circular orbits. Keep in mind that a circle is a unique kind of **ellipse** in which both foci coincide at its centre.

THE LAWS OF PLANETARY MOTION

The laws of planetary motion are as follows:

1 The planets move in elliptical orbits with the Sun at one **focus** (Figure 4.3.2). There is nothing at the other focus.

2 The line connecting a planet to the Sun sweeps out equal areas in equal intervals of time (Figure 4.3.2).

3 The ratio of the square of the period, T, to the cube of the orbital radius, r, is the same for all planets: $\frac{T^2}{r^3} = \text{constant}$.

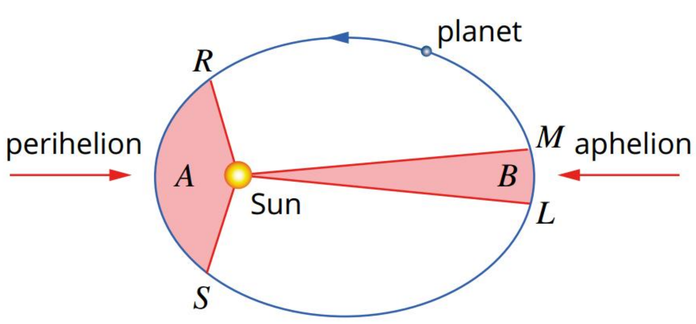


FIGURE 4.3.2 The planets, which are natural satellites of the Sun, orbit in elliptical paths with the Sun at one focus. Their speeds vary continually, and they are fastest when closest to the Sun. A line joining a planet to the Sun will sweep out equal areas in equal times. So, for example, the time it takes to move from R to S is equal to the time it takes to move from L to M, and so area *A* is the same as area *B*.

The first two laws of planetary motion proposed that planets moved in elliptical paths from furthest point (the **aphelion**) to closest point (the **perihelion**). The closer the planet was to the Sun, the faster it moved. This means the orbital radius is not a fixed value, as it would be for a circle, but instead varies as the planet revolves around the sun. To account for this, the **semi-major axis** (Figure 4.3.3) is used in place of the radius. The semi-major axis is half the length of the **major axis**, which is the longest diameter of the ellipse.

In practice, the elliptical orbits of most planets are so close to circular, the difference between the mean orbital radius and the semi-major axis is miniscule and can be ignored. The difference between an elliptical orbit and a circular orbit is known as its **eccentricity**. An eccentricity of 0 describes a circle and as the value increases from 0, the circle becomes more elliptical. To illustrate this, Figure 4.3.4 demonstrates the appearance of ellipses of increasing eccentricity.

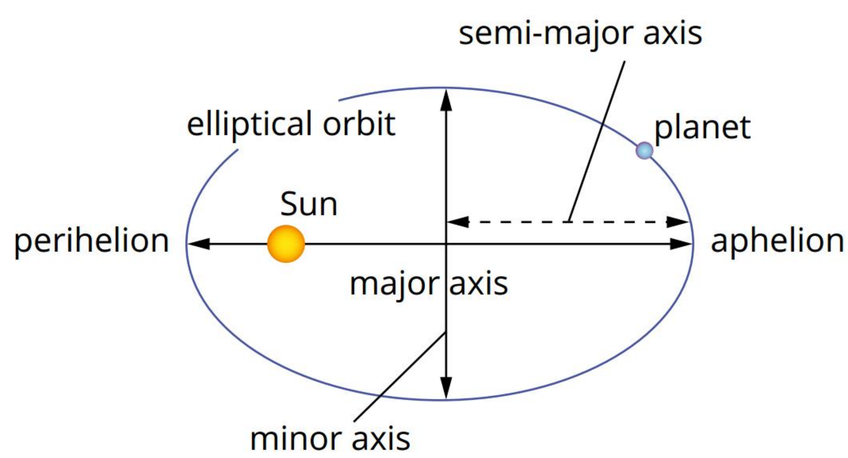


FIGURE 4.3.3 The semi-major axis is half the length of the major axis of the ellipse.

To demonstrate the validity of this approach, understand that the eccentricity of Earth is merely 0.017. Venus is even lower at 0.0068. If ellipses of this eccentricity were included in Figure 4.3.4 they would be visually indistinguishable compared to the circle of eccentricity of 0. Therefore, if a planetary motion problem asks you to perform a calculation simply using a 'radius', do not be concerned about whether this represents a mean radius or a semi-major-axis or some other measurement – the value can be used as is.

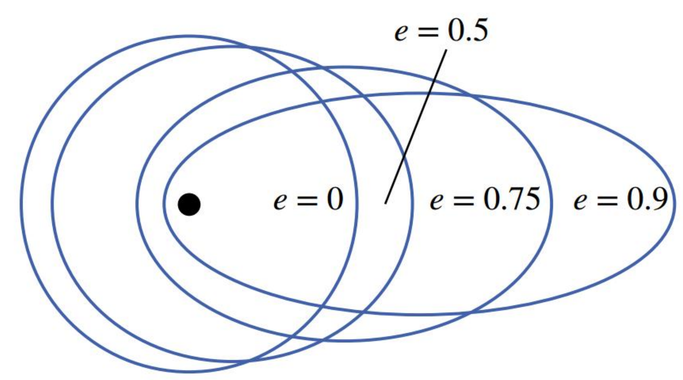


FIGURE 4.3.4 Orbits of increasing eccentricity, from circular to elliptical orbits.

Newton used the laws of planetary motion to justify the inverse square relationship. In fact, the third law of planetary motion can be deduced from the law of universal gravitation. Newton did this by making the same assumption that has been made here; he modelled the orbits with the equations of uniform circular motion.

How Newton derived the third law of planetary motion

It took Kepler many months of laborious calculations to arrive at his third law. Kepler made use of existing observations to derive his empirical rule relating the periods of the planets to their orbital radii. The formulation of his third law required many months of trial-and-error calculations. However, Newton was able to derive the relationship $\frac{T^2}{r^3} = constant$ by combining his law of universal gravitation with the equations of uniform circular motion.

Recall from Chapter 3 that the magnitude of the centripetal force acting on an object in circular motion is given by the equation $F_c = \frac{mv^2}{r}$ and that the law of universal gravitation is given by the equation $F = \frac{GMm}{r^2}$. Newton equated these two expressions as shown below:

First, $v = \frac{2\pi r}{T}$ is substituted into the centripetal force equation:

$$F_c = \frac{mv^2}{r} = \frac{4\pi^2 mr}{T^2}$$

Centripetal force is then equated with the law of universal gravitation:

$$F = F_c$$

$$\frac{GMm}{r^2} = \frac{4\pi^2 mr}{T^2}$$

Cancelling m on both sides and collecting like terms:

$$\frac{GM}{r^3} = \frac{4\pi^2}{T^2}$$

This can be rearranged into the third law of planetary motion:

$$\frac{T^2}{r^3} = \frac{4\pi^2}{GM}$$

$\frac{T^2}{r^3} = \frac{4\pi^2}{GM}$

T is the period of revolution (s).

r is the orbital radius (m)

G is the gravitational constant, $6.67 \times 10^{-11}\ \mathrm{N\,m^2\,kg^{-2}}$

M is the mass of the central body (kg)

If you are using the third law of planetary motion in this form with the $\frac{4\pi^2}{GM}$ term, then you must use SI units for r (m) and T (s).

Worked example 4.3.1

SATELLITES IN ORBIT

Determine the orbital speed of the Moon, assuming it is in a circular orbit of radius 384 000 km around Earth.	
Thinking	**Working**
Ensure that the variables are in their standard units.	$r = 384\,000\,\text{km} = 3.84 \times 10^8\,\text{m}$
Choose the appropriate relationship between the orbital speed, v, and the data that has been provided. The centripetal force, $F_c = \frac{mv^2}{r}$, will be equal to the gravitational force, $F = \frac{GMm}{r^2}$.	$\frac{mv^2}{r} = \frac{GMm}{r^2}$ So, $\frac{v^2}{r} = \frac{GM}{r^2}$
Rearrange to make v the subject of the equation.	$v = \sqrt{\frac{GM}{r}}$
Substitute in values and solve for the orbital speed, v.	$v = \sqrt{\frac{(6.67 \times 10^{-11}) \times (5.97 \times 10^{24})}{3.84 \times 10^8}}$ $= 1.02 \times 10^3\,\text{m s}^{-1}$

➤ Try yourself 4.3.1

SATELLITES IN ORBIT

Determine the orbital speed of a satellite that is in a circular orbit of radius 42 100 km around Earth.

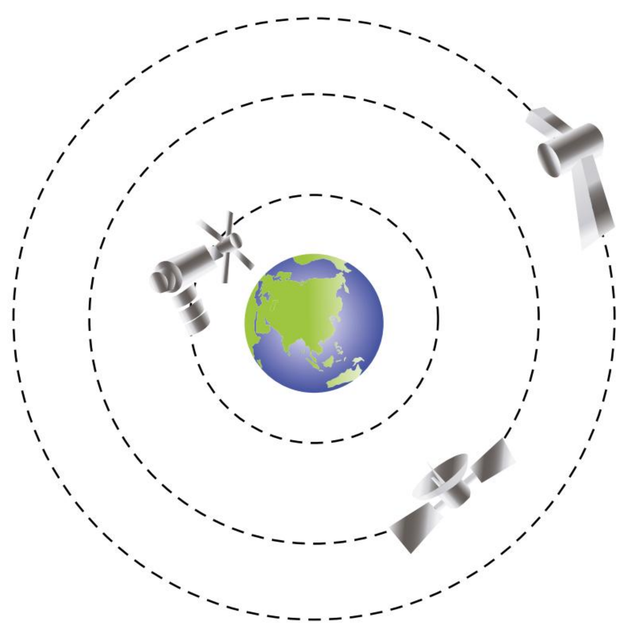


FIGURE 4.3.5 These three satellites are at different distances from Earth and hence, according to the third law of planetary motion, will have different orbital periods. For all three, the ratio of $\frac{T^2}{r^3}$ will equal the same constant value.

For any central mass, M, the term $\frac{4\pi^2}{GM}$ is constant and equal to the ratio $\frac{T^2}{r^3}$ for all its satellites (Figure 4.3.5). So, for example, if you know the orbital radius, r, and period, T, of one of the moons of Saturn, you could calculate $\frac{T^2}{r^3}$ and use this as a constant value for all of Saturn's moons. If you knew the period, T, of a different satellite of Saturn, you could then calculate its orbital radius, r. This idea is represented by an alternate form of the third law of planetary motion which is used to perform these direct comparisons without the need for calculating the $\frac{4\pi^2}{GM}$ term.

$$\frac{T^2_{\text{Titan}}}{r^3_{\text{Titan}}} = \frac{T^2_{\text{Iapetus}}}{r^3_{\text{Iapetus}}}$$

$$\frac{15.9^2}{\left(1.22 \times 10^6\right)^3} = \frac{79^2}{r^3_{\text{Iapetus}}}$$

$$r^3_{\text{Iapetus}} = \frac{79^2 \times \left(1.22 \times 10^6\right)^3}{15.9^2}$$

$$r_{\text{Iapetus}} = \sqrt[3]{\frac{79^2 \times \left(1.22 \times 10^6\right)^3}{15.9^2}}$$

$$r_{\text{Iapetus}} = 3.6 \times 10^6\,\text{km}$$

It is important to understand this only works for objects orbiting the same central Mass. This process could not be used to compare the orbit of the Moon with that of Venus, because the Moon orbits Earth and Venus orbits the Sun, which have different values of M.

For example, Saturn's largest moon, Titan, has a period of 15.9 days and an orbital radius of 1.22×10^6 km. A smaller moon, Iapetus, has a period of 79 days. Its orbital radius can be found using the third law of planetary motion.

Worked example 4.3.2

WORKING WITH THE LAWS OF PLANETARY MOTION

Ganymede is the largest of Jupiter's moons. It has a mass of 1.48×10^{23} kg, an orbital radius of 1.07×10^6 km and an orbital period of 6.18×10^5 s (7.15 days).	
a Calculate the orbital radius (in km) of Europa, another moon of Jupiter, which has an orbital period of 3.55 days.	
Thinking	**Working**
Note down the values for the known satellite. You can work in days and km as this question utilises $\frac{T_a^2}{r_a^3} = \frac{T_b^2}{r_b^3}$	Ganymede: $T_G = 7.15$ days, $r_G = 1.07 \times 10^6$ km Europa: $T_E = 3.55$ days, $r_E = ?$
Recall the third law of planetary motion, replacing the generic a and b with G for Ganymede and E for Europa.	$\frac{T_G^2}{r_G^3} = \frac{T_E^2}{r_E^3}$
Substitute the values into the formula.	$\frac{7.15^2}{(1.07 \times 10^6)^3} = \frac{3.55^2}{r_E^3}$
Make r_E the subject of the equation.	$r_E = \sqrt[3]{\frac{3.55^2 \times (1.07 \times 10^6)^3}{7.15^2}}$
Solve for r_E. The unit for r is km as the original ratio was calculated using km. Note: This value is reasonable. Europa has a shorter period than Ganymede so you should expect Europa to have a smaller orbit than Ganymede.	$r_E = 6.71 \times 10^5$ km
b Calculate the mass of Jupiter using the orbital data for Ganymede.	
Thinking	**Working**
Note down the values for the known satellite. You must work in SI units to find the mass value in kilograms.	$r_G = 1.07 \times 10^9$ m $T_G = 7.15$ days $= 6.18 \times 10^5$ s $m_G = 1.48 \times 10^{23}$ kg $G = 6.67 \times 10^{-11}$ N m^2 kg^{-2} $M_J = ?$

$\frac{T_a^2}{r_a^3} = \frac{T_b^2}{r_b^3}$

T_a is the period of revolution of object a

r_a is the mean orbital radius of object a

T_b is the period of revolution of object b

r_b is the mean orbital radius of object b

If you are using the third law of planetary motion in this form without the $\frac{4\pi^2}{GM}$ term, then you can use *any* suitable units for r and T as long as both r values are the same unit and both T values are the same unit.

Equate centripetal force with the law of universal gravitation and substitute $v = \frac{2\pi r}{T}$.	$F_c = F$ $\frac{mv^2}{r} = \frac{GMm}{r^2}$ $\frac{GMm}{r^2} = \frac{4\pi^2 mr}{T^2}$
Cancel m on both sides and collect like terms.	$\frac{GM}{r^3} = \frac{4\pi^2}{T^2}$
Transpose to make M the subject.	$M = \frac{4\pi^2 r^3}{GT^2}$
Substitute values and solve.	$M_J = \frac{4\pi^2(1.07\times10^9)^3}{6.67\times10^{-11}\times(6.18\times10^5)^2}$ $= 1.90 \times 10^{27}\,\text{kg}$

c Calculate the orbital speed of Ganymede in km s^{-1}.

Thinking	Working
Note the values you will need to use in the equation $v = \frac{2\pi r}{T}$. The answer will be in km s^{-1} if r is expressed in kilometres.	$r_G = 1.07 \times 10^6\,\text{km}$ $T_G = 6.18 \times 10^5\,\text{s}$ $v_G = ?$
Substitute values and solve.	$v_G = \frac{2\pi r}{T}$ $v_G = \frac{2\pi \times (1.07\times10^6)}{6.18\times10^5}$ $= 10.9\,\text{km s}^{-1}$

➤ Try yourself 4.3.2

WORKING WITH THE LAWS OF PLANETARY MOTION

Callisto is the second largest of Jupiter's moons. It is about the same size as the planet Mercury. Callisto has a mass of 1.08×10^{23} kg, an orbital radius of 1.88×10^6 km and an orbital period of 1.44×10^6 s (16.7 days).

a Calculate the orbital radius (in km) of Europa, another moon of Jupiter, which has an orbital period of 3.55 days.

b Calculate the mass of Jupiter using the orbital data for Callisto.

c Calculate the orbital speed of Callisto in km s^{-1}.

4.3 Review

SUMMARY

- Kepler formulated three important laws of planetary motion.
  1. Planets travel around the Sun in elliptical orbits.
  2. Each planet sweeps out equal areas in equal times.
  3. The ratio $\frac{T^2}{r^3}$ is a constant for all planets.
- The third law of planetary motion is useful in determining the radii and periods of planets and exoplanets:

$$\frac{T_a^2}{r_a^3} = \frac{T_b^2}{r_b^3} = \frac{4\pi^2}{GM}.$$

- The equations for uniform circular motion and the law of universal gravitation can be used to derive the laws of planetary motion.

KEY QUESTIONS

For the following questions, note that an AU is an 'astronomical unit' and is equal to the average distance of Earth from the Sun or 150 000 000 km.

Describe

1 State the three laws of planetary motion.

2 Explain why, for most planets, it is equally valid to use the semi-major axis, current distance from the sun, or mean orbital radius for the *r* term in the third law of planetary motion.

Apply

3 Explain what the second law of planetary motion tells you about the speed of a comet as it approaches nearest to the Sun.

4 Explain the effect on the orbital period of Earth if its mass was halved.

5 Explain why it is not possible to use the third law of planetary motion to compare the motion of one of Jupiter's moons with Earth's Moon.

Analyse

6 Calculate Jupiter's period in Earth years. Jupiter orbits the Sun at 5.20 AU.

7 Determine Neptune's distance from the Sun in AU. It takes Neptune 165 years to orbit the Sun.

8 Determine the period in days of a satellite 6.90×10^6 m from Earth's centre. The period of the Moon is 27.3 days and its orbital radius is 3.82×10^8 m.

9 Galileo is credited with the discovery of four of Jupiter's many moons. One of the moons, Ganymede, is 1.07×10^6 km from Jupiter's centre and orbits Jupiter in 7.15 Earth days. Another moon is called Io; it is 4.2×10^5 km from Jupiter's centre. Calculate the period of Io in Earth days.

10 Calculate the mass of Mars given that the smaller of the two Martian moons, Deimos, has a period of 30.35 hours and the radius of its orbit is 23 460 km.

11 The planetoid Pluto is on an elliptical orbit of noticeable eccentricity. Its closest point to the sun is approximately 30 AU while its farthest is approximately 50 AU. Approximate the difference in Pluto's velocity between its farthest and closest points by assuming a circular orbit at these distances. You can find m_{Sun} from the QCAA Formula and data book.

12 The Sun rotates around the centre of the Milky Way at a distance of 2.5×10^{20} m, taking 7.3×10^{15} seconds to make a full rotation. Use this information to estimate the mass of the Galaxy within the Sun's orbit.

Chapter review

04

KEY TERMS

altitude
aphelion
eccentricity
ellipse
field
focus
gravitational constant
gravitational field
gravitational field strength
gravitational force
inverse square law
law of universal gravitation
major axis
perihelion
satellite
semi-major axis

KEY QUESTIONS

For the following questions, note that an AU is an 'astronomical unit' and is equal to the average distance of Earth from the Sun or 150 000 000 km.

Describe

1 Identify the correct statement below about the orbits of natural satellites.

A Earth is a satellite of Mars.
B The Moon is a satellite of the Sun.
C The Sun is a satellite of Earth.
D Earth is a satellite of the Sun.

2 A planetoid, such as Pluto, is a small planet-like object. Identify the best option that lists orbital bodies that can be compared directly using the third law of motion.

A planets and planetoids
B planets and moons
C planets, moons, and satellites
D planets, moons, and planetoids

3 Identify the correct option to complete the following sentence. The second law of planetary motion states:

A Planets travel in circular orbits.
B Orbital velocity is inversely proportional to mass.
C Planetary orbits cover equal areas in equal time.
D The ratio of T^3 to r^2 constant.

4 A person is standing on the surface of the Moon.

a State the equation you would use to calculate the gravitational force experienced by the person.
b State the units your answer will be given in.

Apply

5 Select which is most likely to be the speed of a planet's moon when it is nearest the planet, if the moon has an elliptical orbit and its speed is $20\,\text{km}\,\text{s}^{-1}$ when it is at its average distance from the planet.

A $10\,\text{km}\,\text{s}^{-1}$
B $15\,\text{km}\,\text{s}^{-1}$
C $20\,\text{km}\,\text{s}^{-1}$
D $25\,\text{km}\,\text{s}^{-1}$

6 A person standing on the surface of Earth experiences a gravitational force of 900 N. Determine which of the following gravitational forces this person will experience at a height of two Earth radii above Earth's surface.

A 0 N
B 100 N
C 450 N
D 900 N

7 The planet Jupiter and the Sun exert gravitational forces on each other.

a Describe the force exerted on Jupiter by the Sun compared to the force exerted on the Sun by Jupiter.
b Describe the acceleration of Jupiter caused by the Sun compared to the acceleration of the Sun caused by Jupiter.

Analyse

8 A geostationary satellite orbits Earth once every 24 hours. Use the orbital radius of the Moon (384 000 km) and the orbital period of the moon (27 days) to calculate the orbital radius of the geostationary satellite.

A 3.55×10^5 m
B 4.27×10^4 m
C 4.27×10^7 m
D 3.55×10^8 m

9 An object is experiencing gravitational acceleration of $35.3\,\text{km}\,\text{h}^{-1}\,\text{s}^{-1}$ and a gravitational force of 9.8 kN. The mass of the object is:

A 5.10×10^{-2} kg
B 1.84×10^{-1} kg
C 5.10×10^{1} kg
D 1.84×10^{2} kg

10 The gravitational force of attraction between Saturn and Dione, a moon of Saturn, is equal to 2.79×10^{20} N. Calculate the orbital radius of Dione. Use the following data:

mass of Dione = 1.05×10^{21} kg
mass of Saturn = 5.69×10^{26} kg

11 Of all the planets in the solar system, Jupiter exerts the largest force on the Sun: 4.16×10^{23} N.
Calculate the acceleration of the Sun due to this force, using mass of the Sun = 1.99×10^{30} kg.

12 Calculate the acceleration due to gravity on the surface of Pluto if it has a mass of 1.31×10^{22} kg and a radius of 1190 km.

13 A comet of mass 1100 kg is plummeting towards Jupiter. Jupiter has a mass of 1.90×10^{27} kg and a radius of 7.15×10^{7} m. The comet is about to crash into Jupiter. Calculate the:

- **a** magnitude of the gravitational force that Jupiter and the comet exert on each other
- **b** acceleration of the comet towards Jupiter
- **c** acceleration of Jupiter towards the comet.

14 Calculate the distance from the Sun (which has a mass of 1.99×10^{30} kg), at which an astronaut would experience the same gravitational field strength as they experience at Earth's surface (namely 9.8 N kg^{-1}).

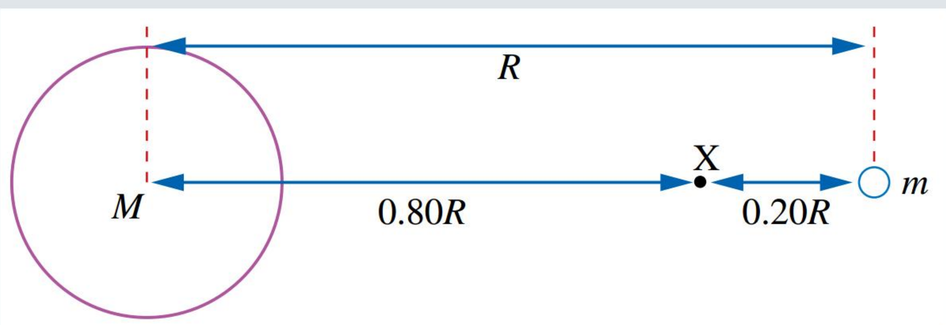
15 Determine what gravitational field strength has been assumed in the following setting. A set of bathroom scales is calibrated so that when the person standing on it has a weight of 6.00×10^{2} N, the scales read 61.5 kg.

16 Calculate the gravitational field strength at the surface of Neptune, which has a radius of 2.48×10^{7} m and a mass of 1.02×10^{26} kg.

17 Earth is a flattened sphere. Its radius at the poles is 6357 km, and at the equator the radius is 6378 km. Earth's mass is 5.97×10^{24} kg.

- **a** Calculate Earth's gravitational field strength at the equator.
- **b** Calculate how much stronger the gravitational field would be at the North Pole compared with the equator using the information in part **a**. Give your answer as a percentage of the strength at the equator to one significant figure.

18 Two stars of masses *M* and *m* are in orbit around each other. As shown in the following diagram, they are a distance *R* apart. A spacecraft located at point X experiences zero net gravitational force from these stars. Calculate the value of the ratio $\frac{M}{m}$.



19 The dwarf planet Ceres is the largest object in the asteroid belt.

- **a** Calculate its period in Earth days if it orbits the Sun in a circular orbit of radius of 2.7675 AU.
- **b** There are thousands of other objects in the asteroid belt, revolving around the Sun at different distances. Determine the range of the asteroid belt from the Sun in AU, if an asteroid year ranges from 1.2×10^{3} days to 2.0×10^{3} days.

20 Atlas, one of Saturn's moons, has an orbital radius of 1.37×10^{5} km and a period of 0.60 days. The largest of Saturn's moons is Titan. It has an orbital radius of 1.20×10^{6} km. Calculate the orbital period of Titan in days.

The following information relates to Questions **21–24**.
Proxima Centauri b is a planet which orbits the star Proxima Centauri (2.4×10^{29} kg) at a radius of approximately 7.5 million kilometres.

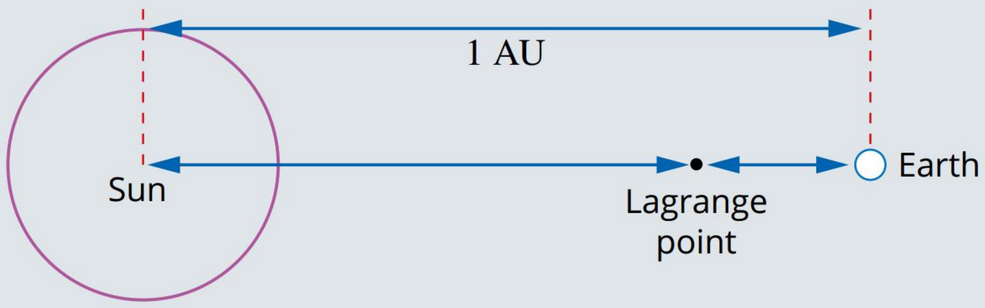
21 Calculate the orbital period of Proxima Centauri b.

22 Calculate the average orbital velocity of Proxima Centauri b.

23 Proxima Centauri c also orbits the star with a period of 1928 days. Calculate its orbital radius.

24 Deduce whether Proxima Centauri c or Proxima Centauri b has the higher orbital velocity.

25 The Lagrange points are positions created by two celestial bodies where the forces of those two bodies are in balance. For the Sun–Earth system, one of these points is located between the Sun and Earth where the gravitational force of Earth and the gravitational force of the Sun cancel each other. Determine the location of this point.

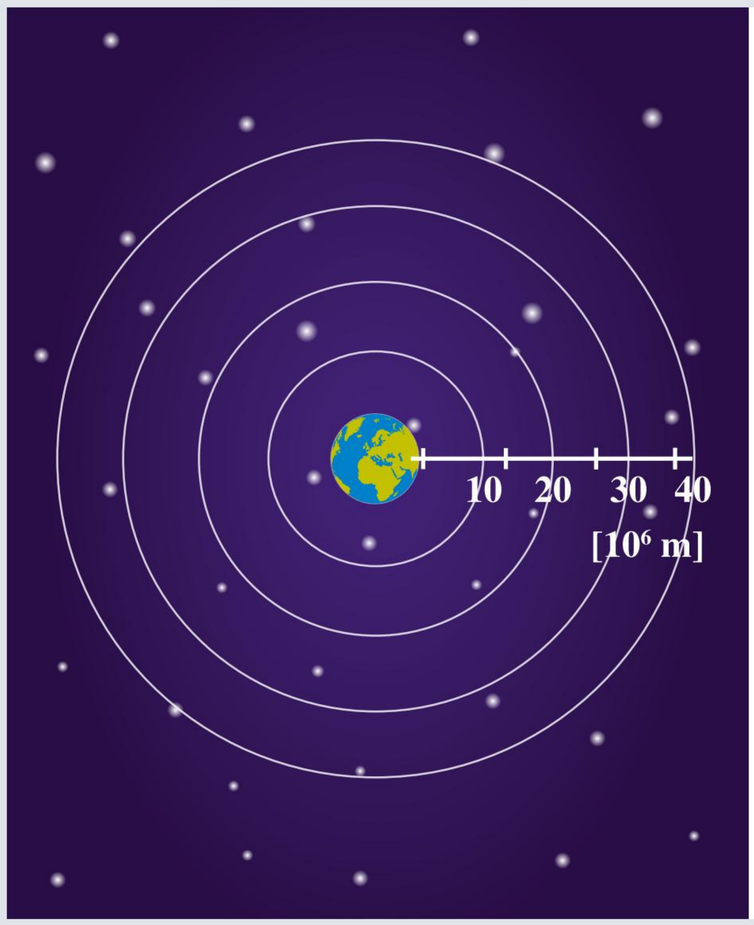


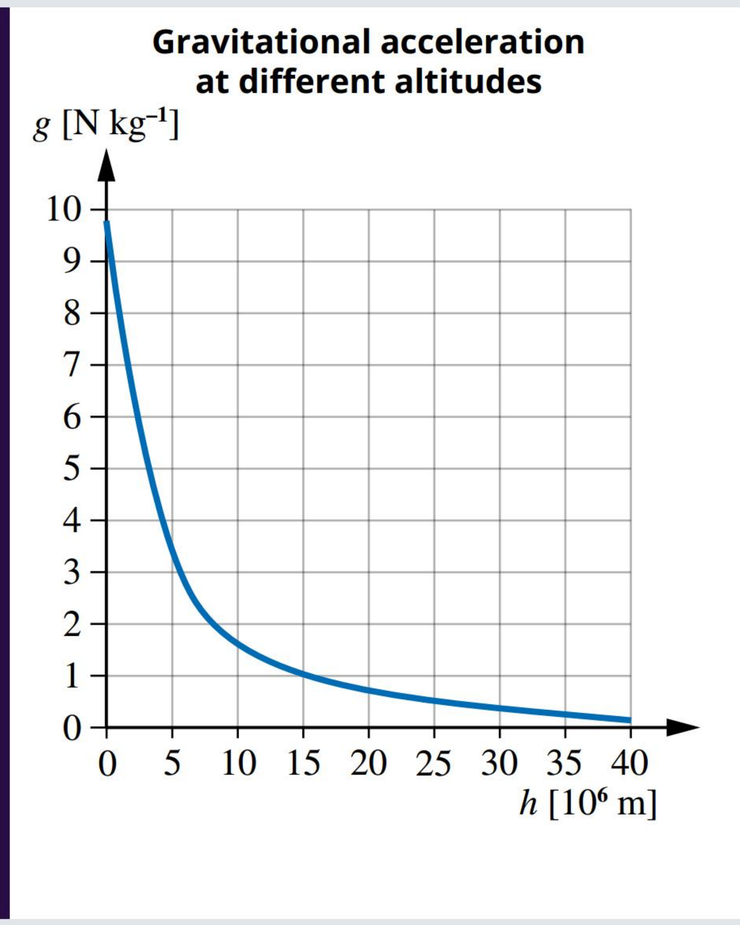
Interpret

26 The value for gravitational acceleration g decreases according to the inverse square law with increasing altitude above Earth, as shown in the diagram and graph. The blue line on the graph gives the value of gravitational acceleration (g) at various altitudes (h).

a Determine the approximate altitude at which the gravitational field strength will be $4\,\text{N kg}^{-1}$ using the graph.

b Compare the gravitational field strength at ground level and at an altitude of 6500 km, using the graph. Predict what the difference will be.





27 The table below shows the period and orbital radius of the solar system's planets:

	Orbital radius (10^6 km)	Orbital period (days)
Mercury	57.9	88.0
Venus	108.2	224.7
Earth	149.6	365.2
Mars	227.9	687.0
Jupiter	778.6	4331.0
Saturn	1433.5	10747.0
Uranus	2872.5	30589.0
Neptune	4495.1	59800.0

a Enter this data into a computer spreadsheet and produce a plot of r vs T.

b Explain why this graph is not a straight line.

c Linearise the dataset by identifying how the x and y variables should be plotted to generate a graph of linear gradient.

d Create a second linearised plot of the data.

e Use the linearised graph to verify if this system adheres to the third law of planetary motion.

f Use the linearised graph to deduce the orbital period of a planet with an orbital radius of 2.2×10^9 km.

g Determine the gradient of the linearised graph.

h Draw a conclusion which quantifies the mass of the Sun.

28 One of the most massive and luminous known stars is called the Pistol Star. It has a mass of approximately 100 times that of the Sun. Determine how long it would take a planet to orbit the Pistol Star if the planet was orbiting the Pistol Star at the same distance that Earth orbits the Sun.

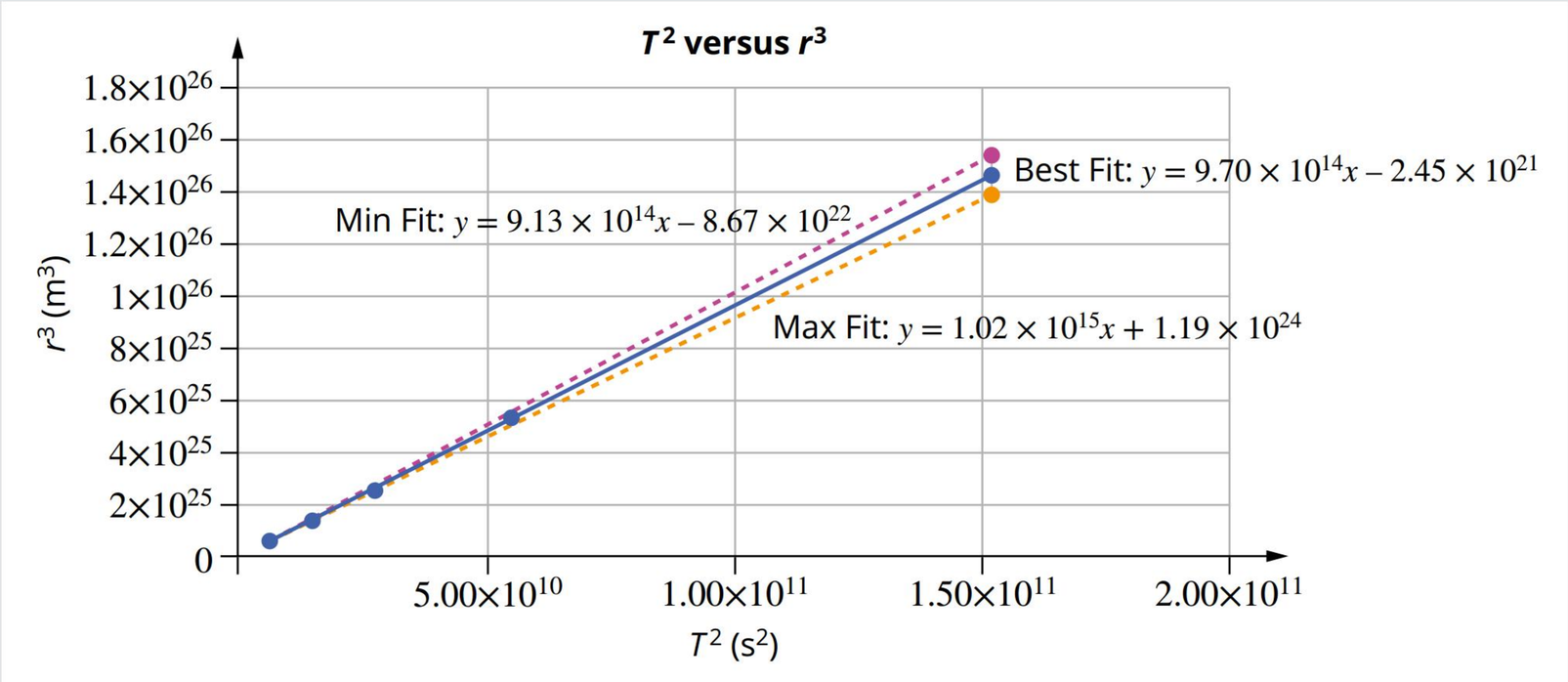
Data analysis

DATA SET 1

The information below applies to Questions **1–3**.

Between 2004 and 2017 the Cassini probe orbited Saturn and collected data about its 146 moons. A sample of the collected orbital period and orbital radius data has been used to generate the plot below.

Note: the mass of Saturn is $M_{Saturn} = 5.68 \times 10^{26}$ kg.



Question 1 (3 marks)

Identify a mathematical relationship between T^2 and r^3, including the uncertainty of the gradient and y-intercept.

Question 2 (4 marks)

Draw a conclusion that quantifies the experimental value of G from the collected data, including the absolute uncertainty in this value. Show your reasoning.

Question 3 (2 marks)

Determine the percentage error in the experimental value of G.

CHAPTER

05 Electric fields

The properties of electrostatics, such as the attraction of small objects when rubbed together, have been known since Thales of Miletus studied charged amber in Greece around 600 BCE. For centuries, the effects of charge build-up were just an intellectual curiosity to scientists and philosophers until the end of 17th century, when its properties were studied and formalised.

We now know that the behaviour of charges and electricity is due to the formation of, and interaction, with electric fields around charges. The study of electric fields and their manipulation has many applications in physics, chemistry and biology, and indeed has vastly shaped the modern world.

The work done by moving charges through electric fields is responsible for all the electrical technology you use, and the disturbance of electric fields with your fingers forms the basis of almost all touchscreen technology used in smartphones and tablets today.

In this chapter you will investigate electric fields, the concepts that apply to forces, charges and fields, and some of the interactions between these closely related phenomena.

Syllabus subject matter

Topic 2 • Electromagnetism

ELECTROSTATICS

- Describe Coulomb's Law. **5.1**
- Solve problems using $F = \frac{1}{4\pi\varepsilon_0}\frac{Qq}{r^2} = \frac{kQq}{r^2}$. **5.1**
- Describe the concepts of electric fields, electric field strength and electrical potential energy. **5.2, 5.3**
- Solve problems involving electric field strength using $E = \frac{F}{Q} = \frac{1}{4\pi\varepsilon_0}\frac{q}{r^2} = \frac{kq}{r^2}$. **5.2**
- Solve problems involving the work done when an electric charge is moved in an electric field using $V = \frac{\Delta U}{q}$. **5.3**

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5.1 Coulomb's law

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- describe Coulomb's law and use it to calculate the force that charged particles exert on each other
- solve problems related to the force, charge and distance between particles.

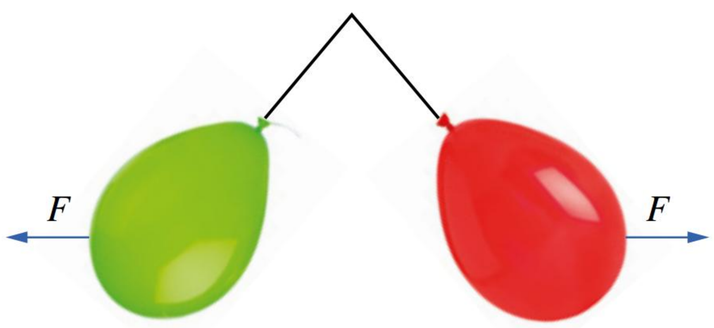


FIGURE 5.1.1 Two similarly charged balloons will repel each other by applying a force on each other.

Recall from *Pearson Physics Queensland Units 1 & 2*, Chapter 4, that a force acts between two charged particles: two like charges will repel each other, and two unlike charges will attract each other. Charles Coulomb first published the quantitative details of this force in 1785. The **electrostatic force**, the force that exists between any combination of electrical charges, can be understood in terms of the force between two '**point charges**' (two charges that can be concentrated or acting from a single point) separated by a certain distance (Figure 5.1.1). The effect of distance on the electric field strength from a single charge and the force created by that field between charges is explored in this section.

THE FORCE BETWEEN CHARGED PARTICLES

Coulomb found that the electrostatic force between two point charges—Q and q—separated by a distance, r, was proportional to the product of the two charges, and inversely proportional to the square of the distance between them.

Coulomb's law can be expressed by the following equation:

$$F = \frac{1}{4\pi\varepsilon_0}\frac{Qq}{r^2} = \frac{kQq}{r^2}$$

where

F is the force on each charged object (N)

Q is the charge on one point (C)

q is the charge on the other point (C)

r is distance between the charged points (m)

ε_0 is the permittivity of free space, which is equal to $8.8542 \times 10^{-12}\,\mathrm{C^2\,N^{-1}\,m^{-2}}$.

$$\frac{1}{4\pi\varepsilon_0} = k = 9 \times 10^9\ \mathrm{N\,m^2\,C^{-2}}$$

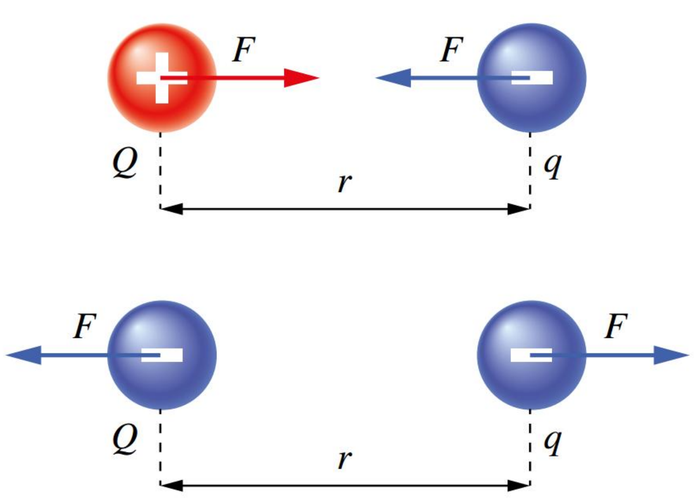


FIGURE 5.1.2 Forces acting between two point charges.

By including the sign of the charges in the calculation, a positive value indicates repulsion and a negative value indicates attraction.

This is another example of an inverse square law, as discussed in Chapter 4 in relation to the gravitational force.

The forces between charges in Coulomb's law are treated the same as forces have been treated in previous topics. The forces are vectors, and the forces between different charged particles will add or subtract as vectors. Vector addition and subtraction can be used to deal with more complex systems of particles and the effect of the electrostatic force between particles can be represented using vector diagrams (Figure 5.1.2).

For collections of more than two particles, Coulomb's law can be used to calculate the force for each individual particle and the resulting vectors can then be added.

Factors affecting the electrostatic force

The force between two charged points is proportional to the product of the two charges. So, if the force between two charged points is 10 N and the charge on one of the points is doubled, then the force between the two points would double to 20 N.

Coulomb's Law is an excellent example of an inverse square law as the force is also inversely proportional to the square of the distance between the two charged points. This means that, if the distance between Q and q is doubled, the force on each point charge will decrease to one quarter of the previous value.

One coulomb in perspective

Coulomb's law can be used to calculate the force between two charges of 1 C each, placed 1 m apart.

$$F = \frac{kQq}{r^2} = k \times \frac{1.0 \times 1.0}{1^2} = 9.0 \times 10^9 \text{N}$$

The force is approximately 10^{10} N. This is equivalent to the weight provided by a mass of 918 000 tonnes (Figure 5.1.3).

This demonstrates that a 1 C charge is a huge amount of charge. In reality, the amount of charge that can be placed on ordinary objects is a tiny fraction of a coulomb. Even a highly charged Van de Graaff generator will have only a few microcoulombs ($1\,\mu\text{C} = 10^{-6}$ C) of excess charge.

FIGURE 5.1.3 Two 1 C charges 1 m apart would produce a force of 10^{10} N, which is almost twice the weight of the Sydney Harbour Bridge.

Worked example 5.1.1

USING COULOMB'S LAW TO CALCULATE FORCE

Two small spheres A and B act as point charges separated by 10.0 cm in air. Calculate the force on each point charge, if A has a charge of 3.00 μC and B has a charge of −45.0 nC.

Thinking	Working
Convert all values to SI units.	$Q = 3.00 \times 10^{-6}$ C $q = -45.0 \times 10^{-9} = -4.50 \times 10^{-8}$ C $= 0.100$ m
State Coulomb's law.	$F = \frac{1}{4\pi\varepsilon_0}\frac{Qq}{r^2} = \frac{kQq}{r^2}$
Substitute the values for Q, q, r and ε_0 into the equation and calculate the answer.	$F = 9 \times 10^9 \times \frac{(3.00 \times 10^{-6}) \times (-4.50 \times 10^{-8})}{0.100^2}$ $= -0.122$ N
Assign a direction based on a negative force being attraction and a positive force being repulsion.	$F = 0.122$ N attraction

➤ Try yourself 5.1.1

USING COULOMB'S LAW TO CALCULATE FORCE

Two small spheres A and B act as point charges separated by 75.0 mm in air. Calculate the force on each point charge if A has a charge of 475 nC and B has a charge of 833 pC.

Worked example 5.1.2

USING COULOMB'S LAW TO CALCULATE CHARGE

Two small positive point charges with equal charge are separated by 1.25 cm in air. Calculate the charge on each point charge if there is a repulsive force of 6.48 mN between them.

Use $k = 9 \times 10^9\,\mathrm{N\,m^2\,C^{-2}}$.

Thinking	Working
Convert all values to SI units.	$F = 6.48 \times 10^{-3}\,\mathrm{N}$ $r = 1.25 \times 10^{-2}\,\mathrm{m}$
State Coulomb's law.	$F = \dfrac{kQq}{r^2}$
Substitute the values for F, r and k into the equation and calculate the answer.	$Qq = \dfrac{Fr^2}{k} = \dfrac{(6.48\times10^{-3})\times(1.25\times10^{-2})^2}{9\times10^9}$ $= 1.126 \times 10^{-16}$ As $Q = q$: $Q^2 = 1.126 \times 10^{-16}$ $Q = \sqrt{1.126\times10^{-16}}$ $= +1.06 \times 10^{-8}\,\mathrm{C}$ $q = +1.06 \times 10^{-8}\,\mathrm{C}$

➤ Try yourself 5.1.2

USING COULOMB'S LAW TO CALCULATE CHARGE

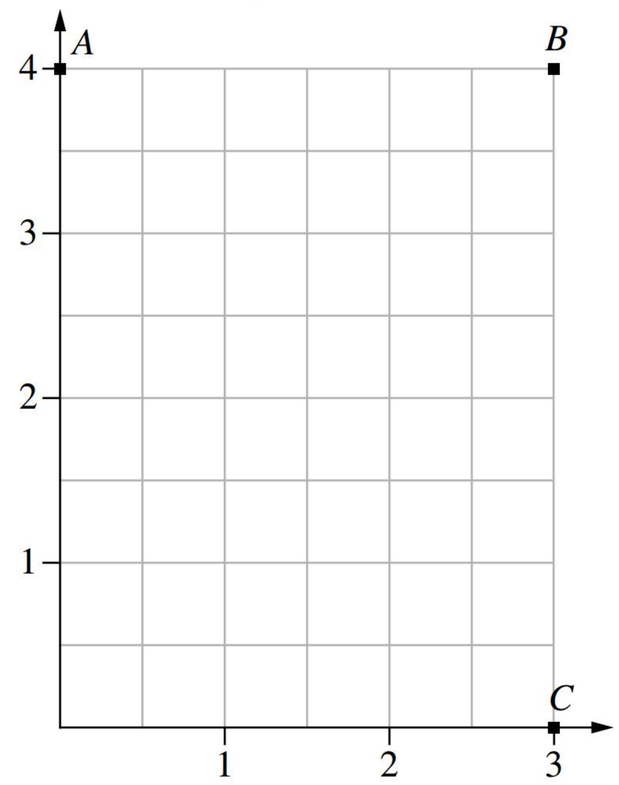
Two small point charges are charged by transferring several electrons from Q to q. The charges on the two points are equal and opposite, and the point charges are separated by 12.7 mm in air. Calculate the charge on Q and q, if there is an attractive force of 22.5 μN between them.

Use $k = 9 \times 10^9\,\mathrm{N\,m^2\,C^{-2}}$.

Worked example 5.1.3

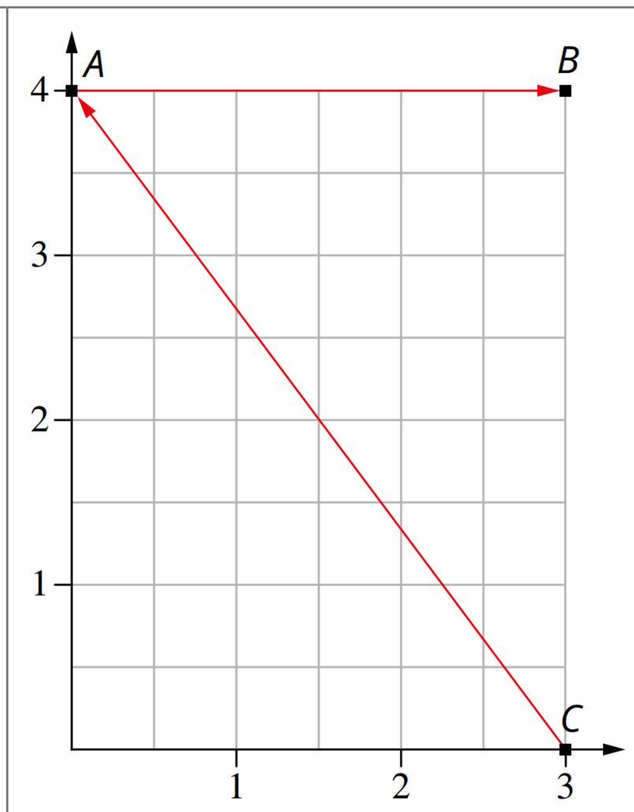
USING COULOMB'S LAW TO CALCULATE THE FORCE BETWEEN MULTIPLE CHARGES

Three point charges A, B and C are separated as shown in the diagram below.



Calculate the magnitude and direction of the net force acting on charge A, given that $q_A = -1.6 \times 10^{-19}$ C, $q_B = +1.6 \times 10^{-19}$ C, and $q_C = -1.6 \times 10^{-19}$ C. The distance scale is in mm.

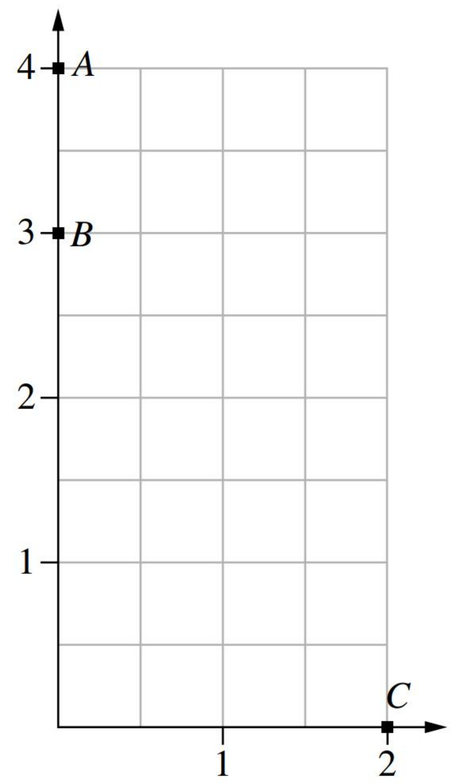
Thinking	Working
Write down the distance between A and B in SI units.	From the grid, AB = 3 mm = 3×10^{-3} m.
Write down the distance between A and C in SI units.	Using Pythagoras: $c^2 = a^2 + b^2$ $c = \sqrt{a^2 + b^2}$ $= \sqrt{9 + 16}$ AC = 5×10^{-3} m
Write down each of the charges in Coulombs.	$q_A = -1.6 \times 10^{-19}$ C $q_B = 1.6 \times 10^{-19}$ C $q_C = -1.6 \times 10^{-19}$ C
Calculate the force acting on A by B.	$F_{BA} = \frac{kQq}{r^2}$ $= \frac{(9 \times 10^9) \times (-1.6 \times 10^9) \times (1.6 \times 10^9)}{(3.0 \times 10^{-3})^2}$ $= -2.56 \times 10^{-23}$ N $= 2.56 \times 10^{-23}$ N attraction
Calculate the force acting on A by C.	$F_{BA} = \frac{kQq}{r^2}$ $= \frac{(9.0 \times 10^9) \times (-1.6 \times 10^{-19})^2}{(5.0 \times 10^{-3})^2}$ $= 9.216 \times 10^{-24}$ N $= 9.216 \times 10^{-24}$ N repulsion

Draw arrows to designate the vectors of the two forces.	
Add the two-dimensional vectors to give the resultant force on A. There is only one force in the vertical direction, so this comprises the net vertical force. To get the net horizontal force, add the horizontal components of the vectors.	The vector CA is at an angle of $\theta = \tan^{-1}\left(\frac{4}{3}\right) = 53.1^\circ$ above the horizontal, so its horizontal component is: $F_H = (9.216 \times 10^{-24}) \times \cos 53.1^\circ$ $= 5.5296 \times 10^{-24}$ N Similarly, its vertical component is: $F_V = (9.216 \times 10^{-24}) \times \sin 53.1^\circ$ $= 7.373 \times 10^{-24}$ N $F_{H\ net} = -5.5296 \times 10^{-24} + 2.56 \times 10^{-23}$ $= 2.01 \times 10^{-23}$ N So the net force acting on A is 7.37×10^{-24} N in the positive vertical direction, and 2.01×10^{-23} N in the positive horizontal direction.
Use Pythagoras to calculate the final net force and its angle above the horizontal.	$F = \sqrt{F_H^2 + F_V^2}$ $= \sqrt{\left(2.01 \times 10^{-23}\right)^2 + \left(7.37 \times 10^{-24}\right)^2}$ $= 2.1 \times 10^{-23}$ N $\theta = \tan^{-1}\left(\frac{7.37 \times 10^{-24}}{2.01 \times 10^{-23}}\right)$ $= 20^\circ$ $F_{net} = 2.1 \times 10^{-23}$ N at an angle of 20° above the positive horizontal line.

➤ Try yourself 5.1.3

USING COULOMB'S LAW TO CALCULATE THE FORCE BETWEEN MULTIPLE CHARGES

Three point charges A, B and C are separated as shown in the diagram below.



Calculate the magnitude and direction of the net force acting on charge A when $q_A = -1.0 \times 10^{-8}$ C, $q_B = +0.5 \times 10^{-8}$ C and $q_C = -2.5 \times 10^{-8}$ C. Length units are in mm.

5.1 Review

SUMMARY

- Coulomb's law describes the force exerted by electrostatically charged objects on other electrostatically charged objects.
- Coulomb's law for the force between two charges q and Q separated by a distance of r is:

$$F = \frac{1}{4\pi\varepsilon_0}\frac{Qq}{r^2} = \frac{kQq}{r^2}$$

- The constant, ε_0, in Coulomb's law is the permittivity of free space, and has a value of $8.8542 \times 10^{-12}\,C^2\,N^{-1}\,m^{-2}$ and $\frac{1}{4\pi\varepsilon_0} = k = 9 \times 10^9\ N\,m^2\,C^{-2}$
- In more complex systems of more than two particles, Coulomb's law can be used to calculate the force for each individual particle and the resulting force between particles can be found by vector addition.

KEY QUESTIONS

Describe

1 Describe 'Coulomb's law' in terms of the forces on charged particles.

2 The mathematical form of Coulomb's Law is $F = \frac{kQq}{r^2}$.

Describe the relationship between electrostatic force, charges, and the distance between the charges.

3 Identify the three quantities on which the force between two charged particles depends.

5.1 Review *continued*

Apply

4 A charge of $+q$ is placed a distance r from another charge also of $+q$. A repulsive force of magnitude F is found to exist between them.
Describe the changes, if any, that will occur to the force between two charges in the following situations, by identifying the correct options from the text in italics.

a If both charges are doubled to $+2q$, the force will *halve / double / quadruple / quarter* and *repel / attract*.

b If the distance between the charges is halved to $0.5r$, the force will *halve / double / quadruple / quarter* and *repel / attract*.

5 State the proportion by which the electrostatic force between two point charges, increases or decreases when the distance between the two charges is

a doubled

b tripled

6 Two positive point charges are separated by a distance, x. Draw a force diagram for each of the charges, showing only electrostatic forces. State whether the force will be attractive or repulsive.

Analyse

7 Determine the net force acting on a positive unit charge with one negative unit charge 1 m to its left and one negative unit charge 1 m to its right.

8 Determine the force that would be exerted on a single negative elementary charge (i.e. an electron's charge) surrounded by four equidistant positive elementary charges.

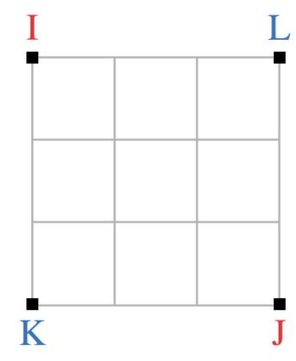
9 A negative charge of −2.0 C and a positive charge of 1.0 C are separated by a distance of 50 m. Calculate the force between the two charges.

10 A hydrogen atom consists of a proton and an electron separated by a distance of 53 pm (picometres). Calculate the force applied to a proton carrying a charge of $+1.60 \times 10^{-19}$ C by an electron carrying a charge of -1.60×10^{-19} C.

11 Two negative charges, that are both -3.0×10^{-6} C, push each other apart with a force of 19.2 N. Determine the distance between the two charges.

12 Calculate the repulsive force on each proton in a helium nucleus separated in a vacuum by a distance of 2.50 fm.
$1\text{ fm} = 1 \times 10^{-15}$ m and $q_p = +1.6 \times 10^{-19}$ C.

13 Two positive (red, I and J) and two negative (blue, K and L) elementary charges are fixed on the edges of a 1.0 m × 1.0 m square table as shown below.



Calculate the net force acting on charge I (with direction in terms of horizontal and vertical components).

5.2 Electric fields

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- describe what an electric field is and the strength of electric fields
- explain how an electric field affects the behaviour of other charged particles
- predict how a charged particle will induce an electric field of its own
- draw field lines to represent the electric fields of various systems
- solve problems involving the electric field strength around charges.

There are four fundamental forces in nature that act at a distance, that is, they can exert a force on an object without making any physical contact with it. These are called non-contact forces, and include the strong nuclear force, the weak nuclear force, the electromagnetic force and the gravitational force.

To understand these forces, scientists use the idea of a field. A field is a region of space in which objects experience a force due to a physical property related to the field. Gravity, electricity and magnetism can all be described by fields. Chapter 4 described the direction, shape and strength of gravitational fields around a mass. In this section the electric field will be explained.

ELECTRIC FIELD LINES

An **electric field** surrounds positive and negative charges, and exerts a force on other charges within the field. An electric field is a vector quantity; it has both direction and strength.

To visualise electric fields around charged objects you can use electric **field lines**. Some field lines are already visible. For example, the charged plasma in Figure 5.2.1 follows the lines of the electric field, and the girl's hair in Figure 5.2.2 is tracing out the path of the field lines. Diagrams of field lines can also be constructed.

Field lines are drawn with arrowheads indicating the direction of the force that a small positive test charge would experience if it were placed in the electric field. Therefore, field lines point away from positively charged objects and towards negatively charged objects. Usually, only a few representative lines are drawn.

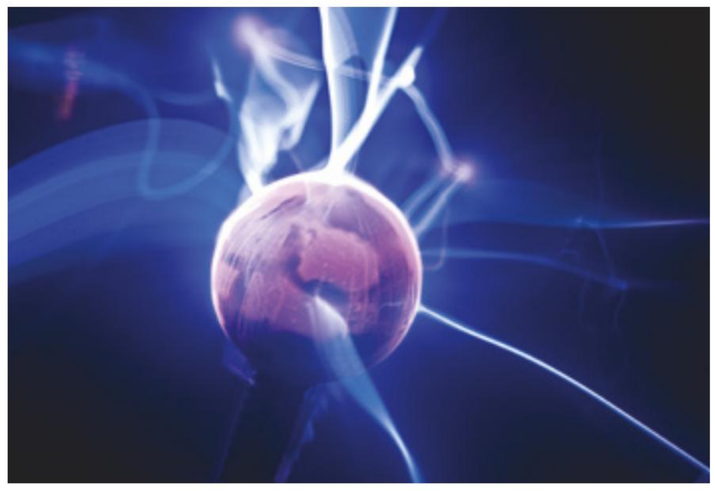


FIGURE 5.2.1 Charged plasma follows lines of the electric field produced by a Van de Graaff generator.

FIGURE 5.2.2 The girl's hair follows the lines of the electric field produced when she became charged while sliding down the plastic slide.

> The density of field lines (how close they are together) is an indication of the relative strength of the electric field.

Guidelines for drawing electric field lines

While the drawing of electric fields is not specifically required, knowing how electric fields are drawn can aid considerably in understanding what these diagrams are explaining. When drawing electric field lines (in two dimensions) around a charged object, there are a few guidelines that need to be followed.

- The space between field lines indicates the strength of the field. The closer the lines, the stronger the field.
- Electric field lines go from positively charged objects to negatively charged objects.
- Electric field lines start and end at 90° to the surface, with no gap between the lines and the surface.
- Field lines can never cross; if they did, it would indicate that the field is in two directions at that point, which can never happen.
- Around point charges you should draw at least eight field lines: top, bottom, left, right and another field line in between each of these, like spokes on a wheel.
- Between two point charges, the direction of the field at any point is the resultant field vector determined by adding the field vectors due to each of the two point charges.

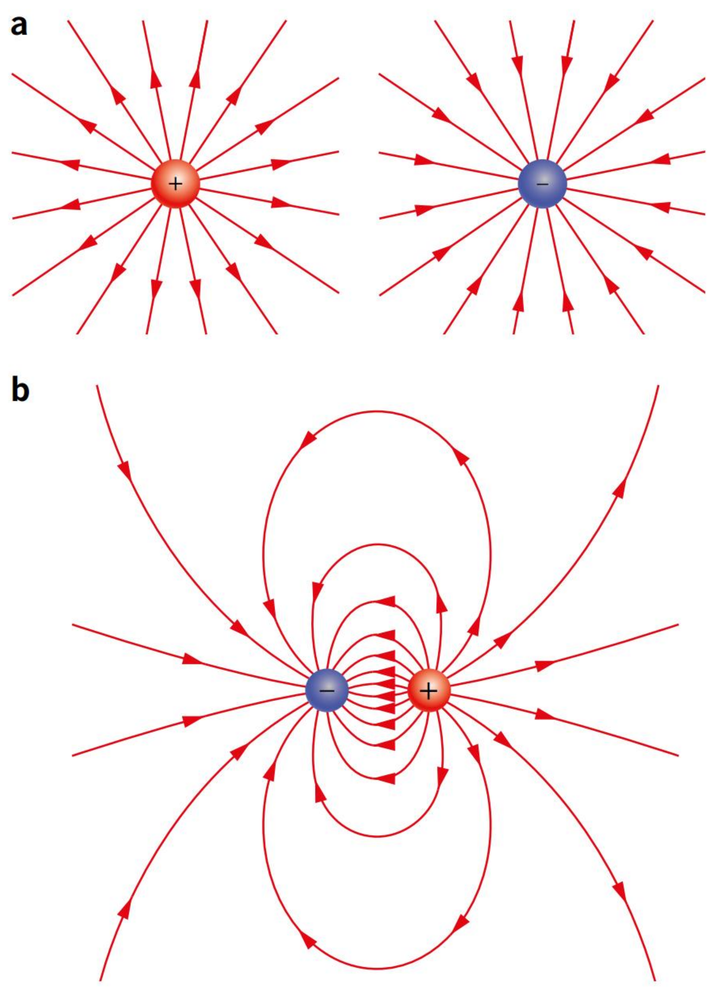


FIGURE 5.2.3 (a) Positive point charges have their electric field lines pointing radially outwards. Negative point charges have their electric field lines pointing radially inwards. (b) When positive and negative charges are placed together they form an electric dipole. Their field lines interact in a more complex fashion than in (a).

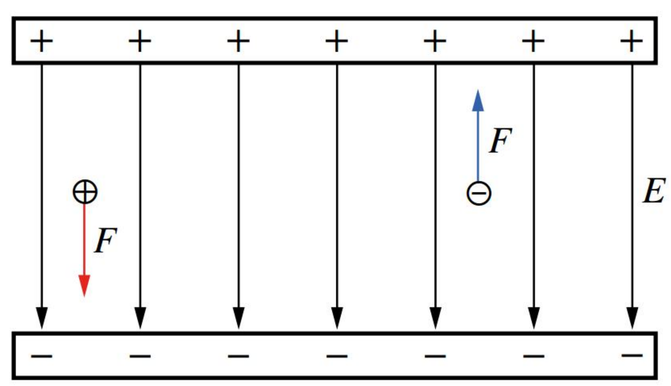


FIGURE 5.2.4 The direction of the electric field, *E*, indicates the direction in which a force would act on a positive charge. A negative charge would experience a force in the opposite direction to the field.

- Between two oppositely charged parallel plates, the field lines between the plates are evenly spaced and are drawn straight from the positive plate to the negative plate.
- Always remember that these drawings are two-dimensional representations of a three-dimensional field.

Figure 5.2.3 shows some examples of how to draw electric field lines. Figure 5.2.3a shows the electric fields around positive and negative point charges; Figure 5.2.3b shows the electric field of an electric dipole (pair of oppositely charged poles).

STRENGTH OF THE ELECTRIC FIELD

The distance between adjacent field lines indicates the strength of the field. Around a point charge, the field lines are closer together near the charge and further apart away from the charge. You can see this in the field-line diagrams in (Figure 5.2.3). The **electric field strength**, *E*, decreases as the distance from a point charge increases.

A uniform electric field is established between two parallel metal plates that are oppositely charged. The field strength is constant at all points within a uniform electric field, so the field lines are parallel.

If a charged particle, such as an electron, is placed within such an electric field, it experiences a force. The direction of the field and the sign of the charge allows the direction of the force to be determined.

Figure 5.2.4 shows a positive test charge (proton) and a negative test charge (electron), within a uniform electric field. Recall that the direction of an electric field is defined as the direction of the force that a positive charge would experience within the electric field. So, an electron will experience a force in the opposite direction to the electric field, while a proton will experience a force in the same direction as the field.

The magnitude of the electric field can be determined using the equation:

$$E = \frac{F}{Q}$$

where

E is the strength of the electric field ($N\,C^{-1}$).

F is the force on the charged particle (N)

Q is the charge of the object experiencing the force (C)

This equation illustrates that the electric field strength *E* is proportional to the force, *F*, acting on the charge. The force on the charged particle will cause the charged particle to accelerate in the field. This means that the particle could increase its velocity, decrease its velocity, or change its direction while in the field.

Worked example 5.2.1

USING $E = \frac{F}{Q}$

Calculate the magnitude of the uniform electric field that would cause a force of 5.00×10^{-21} N on an electron. ($q_e = -1.60 \times 10^{-19}$ C)	
Thinking	**Working**
Use the relationship for electric field strength.	$E = \frac{F}{Q}$
Substitute the values for *F* and *Q* into the equation and calculate the answer. (As only magnitude is required, *Q* can be kept positive.)	$E = \frac{5.00 \times 10^{-21}}{1.60 \times 10^{-19}}$ $= 3.13 \times 10^{-2}\,N\,C^{-1}$

➤ Try yourself 5.2.1

USING $E = \frac{F}{Q}$

Calculate the magnitude of the uniform electric field that creates a force of 9.00×10^{-23} N on a proton.
($q_p = +1.60 \times 10^{-19}$ C)

The electric field at a distance from a charge

The electric field can also be calculated at a distance from a single point charge. Recalling that $F = \frac{1}{4\pi\varepsilon_0}\frac{Qq}{r^2} = \frac{kQq}{r^2}$ and noting that $E = \frac{F}{Q}$ then:

The magnitude of the electric field at a distance from a single point charge is given by:

$$E = \frac{1}{4\pi\varepsilon_0}\frac{q}{r^2} = \frac{kq}{r^2}$$

where

E is the strength of the electric field around a point ($\mathrm{N\,C^{-1}}$)

q is the charge on the point creating the field (C)

r is the distance from the charge (m)

ε_0 is the permittivity of free space ($8.8542 \times 10^{-12}\,\mathrm{C^2\,N^{-1}\,m^{-2}}$)

$$\frac{1}{4\pi\varepsilon_0} = k = 9 \times 10^9\ \mathrm{N\,m^2\,C^{-2}}$$

Note that an electric field at each point is defined by how a particle *would* interact with it at that position.

This relationship is another example of an inverse square law; that is:

$$E \propto \frac{1}{r^2}$$

Worked example 5.2.2

ELECTRIC FIELD OF A SINGLE POINT CHARGE

Calculate the magnitude and direction of the electric field at a point P at a distance of 20.0 cm below a negative point charge, q, of 2.0×10^{-6} C.	
Thinking	**Working**
Convert units to SI units as required.	$q = -2.0 \times 10^{-6}$ C $r = 20.0$ cm $= 0.200$ m
Substitute the known values to find the magnitude of E using $E = \frac{kq}{r^2}$.	$E = \frac{kq}{r^2}$ $E = \frac{(9 \times 10^9) \times (2.0 \times 10^{-6})}{0.2^2}$ $= 4.5 \times 10^5\ \mathrm{N\,C^{-1}}$
The direction of the field is defined as that acting on a positive test charge. Point P is below the charge.	Since the charge is negative, the direction will be towards the charge q, or upwards.

➤ Try yourself 5.2.2

ELECTRIC FIELD OF A SINGLE POINT CHARGE

Calculate the magnitude and direction of the electric field at point P at a distance of 15 cm to the right of a positive point charge, q, of 2.0×10^{-6} C.

5.2 Review

SUMMARY

- An electric field is a region of space around a charged object in which another charged object will experience a force.
- Electric fields are represented using field lines.
- Electric field lines point in the direction of the force that a positive charge within the field would experience.
- A positive charge experiences a force in the direction of the electric field and a negative charge experiences a force in the opposite direction to the field.
- The spacing between the field lines indicates the strength of the field. The closer together the lines are, the stronger the field.
- A stronger electric field indicates that the field will exert a larger electrostatic force on a charged object.
- Electric field strength can be expressed as $E = \frac{F}{Q}$
- Around point charges the electric field radiates in all directions (three dimensionally).
- The magnitude of the electric field at a distance from a single point charge is given by $E = \frac{1}{4\pi\varepsilon_0}\frac{q}{r^2} = \frac{kq}{r^2}$
- Between two oppositely charged parallel plates, the field lines are parallel and therefore the field has a uniform strength.

KEY QUESTIONS

Describe

1 Recall whether the re-stated guidelines below for drawing electric field lines are true or false.

a Electric field lines start and end at 90° to the surface, with no gap between the lines and the surface.

b Field lines can cross; this indicates that the field is in two directions at that point.

c Electric fields go from negatively charged objects to positively charged objects.

d Around small charged spheres called point charges you should draw at least eight field lines: top, bottom, left, right and in between each of these.

e Around point charges the field lines radiate like spokes on a wheel.

f Between two point charges the direction of the field at any point is the field due to the closest of the two point charges.

g Between two oppositely charged parallel plates the field between the plates is evenly spaced and is drawn straight from the negative plate to the positive plate.

Apply

2 Describe how the strength of an electric field changes with distance from a charge.

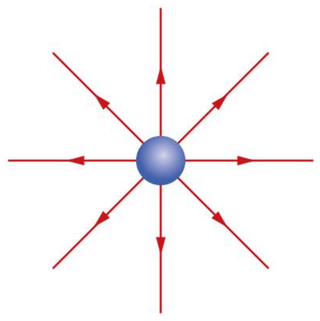
3 Describe the direction of the force acting on a negative charge with respect to the direction of the field.

4 Describe the two effects that an electric field may have on the motion of a charged particle.

The following information relates to Questions **5**–**8**.

Based on your understanding of electric fields, identify the charge on the object, or objects, in each of the following electric field diagrams.

5



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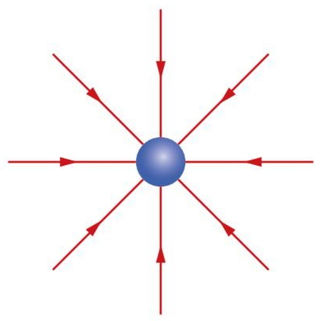

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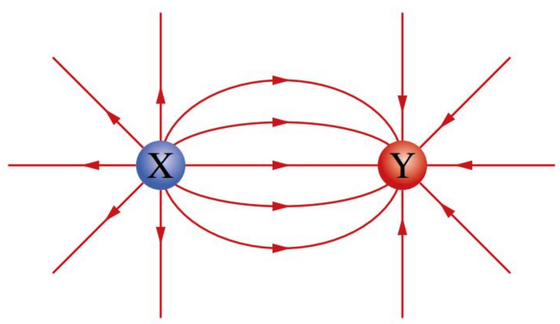

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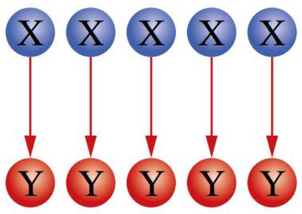
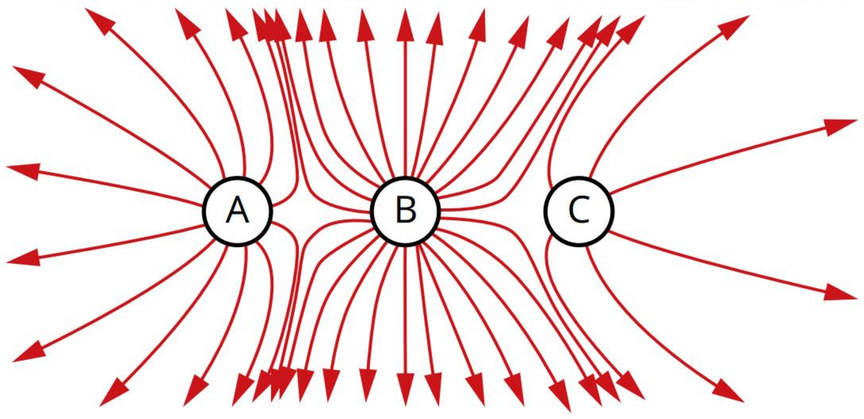


9 The following diagram shows three point charges, A, B and C.

First, identify whether each charge is positive or negative.

Then, rank the charge on each from highest to lowest.



Analyse

10 Calculate the force applied to a balloon carrying a charge of 5.00 mC in a uniform electric field of $2.50\,\mathrm{N\,C^{-1}}$.

11 Calculate the charge on a plastic disc if it experiences a force of 0.025 N in a uniform electric field of $18\,\mathrm{N\,C^{-1}}$.

12 Calculate the acceleration of an electron in a uniform electric field of $3.25\,\mathrm{N\,C^{-1}}$. The mass of an electron is 9.109×10^{-31} kg and its charge is -1.60×10^{-19} C.

5.3 Electrical potential energy

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- describe the important quantities of electric potential and electrical potential energy
- calculate the work done on or by a charged particle as it moves through an electric field using $V = \frac{\Delta U}{q}$.

As a charge in an electric field experiences an unbalanced force, some work must be done by the electric field on the charge. In discussing work done by an electric field two related but distinct quantities are introduced.

- **Electrical potential energy** (U) is a form of energy that is stored in a field.
- **Electric potential** (V) is defined as the energy required per unit charge to move a point charge from a reference point to a place in the electric field.

$$V = \frac{\Delta U}{q}$$

where

V is the electric potential ($J\,C^{-1}$) or volts (V)

ΔU is the difference in electrical potential energy stored in the field between a test charge at a reference point and a test charge at a particular point

q is the charge of the point charge (C).

With the electric potential at infinity defined as zero, the change in electrical potential energy is equal to the work done (W) on a positive point charge or on the field (J). Recalling that $\Delta U = W$ then the equation can be rewritten as $V = \frac{W}{q}$. This equation was introduced in *Pearson Physics Queensland Units 1 & 2*.

Worked example 5.3.1

CALCULATING ELECTRIC POTENTIAL

A test charge of $+3.2 \times 10^{-19}$ C is placed at a point near the charged sphere of a Van de Graaf generator. If the test charge is found to have 6.0×10^{-18} J of electrical potential energy, calculate the electric potential, V.

Thinking	Working
Identify the variables presented in the question.	$q = +3.2 \times 10^{-19}$ C $\Delta U = 6.0 \times 10^{-18}$ J
Substitute the values into the equation $V = \frac{\Delta U}{q}$	$V = \frac{\Delta U}{q}$ $= \frac{6.0 \times 10^{-18}}{3.2 \times 10^{-19}}$ $= 19$ V

➤ Try yourself 5.3.1

CALCULATING ELECTRIC POTENTIAL

A test charge of $+1.6 \times 10^{-19}$ C is placed at a point in a uniform electric field. If the test charge is found to have 3.2×10^{-18} J of electrical potential energy, calculate the electric potential, V.

POTENTIAL DIFFERENCE

Consider two parallel plates (Figure 5.3.1) in which the positive plate is at a potential (V) and the other negative plate is earthed, which is defined as having zero potential. The difference in potential between these two plates is called the **potential difference** (V).

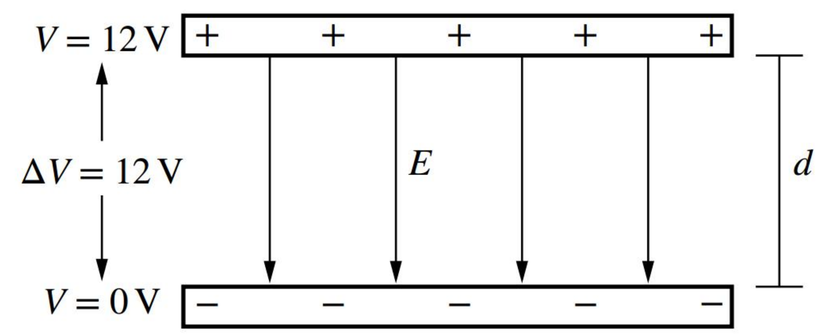


FIGURE 5.3.1 The potential difference between two points in a uniform electric field

WORK DONE BY OR ON AN ELECTRIC FIELD

Electric field strength can be expressed by the equation:

$$E = \frac{F}{Q}$$

So, $F = EQ$

Work is equal to force over a displacement, $W = Fs$

If the distance is given as the value d, then this equation can be written as $W = Fd$.

Using $F = EQ$, then the work done in an electric field is given by the equation:

$$W = Fd = QEd$$

where

W is the work done on the point charge or on the field (J)

Q is the charge of the point charge (C)

E is the strength of the electric field ($\mathrm{N\,C^{-1}}$)

d is the distance between two points in the field (m).

When calculating work done, note that work can be done either by the electric field on a charged object, or on the electric field by forcing the object to move.

For example, if a charged object is moving in the direction it would naturally tend to go within an electric field, then work is done by the field. So, when a positive point charge is moved in the direction of the electric field, the electric field has done work on the point charge. (Refer to q_2 in Figure 5.3.2.)

When work is done by a charged object on an electric field, the object is forced to move against the direction it would naturally go. Work has been done on the field by forcing the object to move. For example, if a force causes a positive charge to move towards the positive plate within a uniform electric field, work has been done on the electric field by forcing the object to move. (See q_1 in Figure 5.3.2.)

If a charge does not move any distance parallel to the field, then no work is done on or by the field. (See q_3 in Figure 5.3.2.)

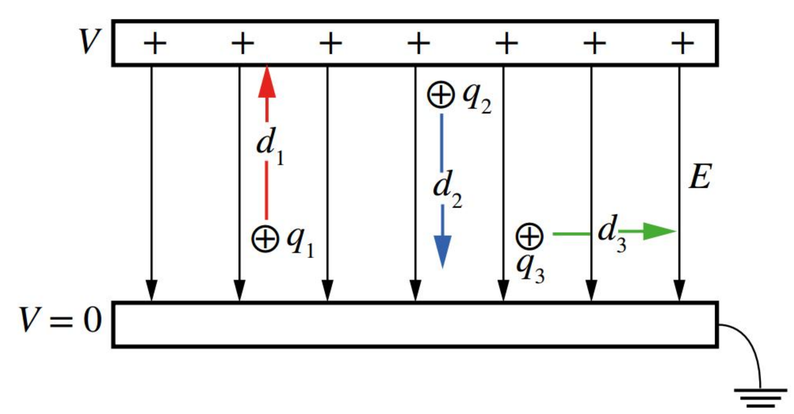


FIGURE 5.3.2 Work is being done on the field by moving q_1 and work is being done by the field on q_2. No work is done on q_3 since it is moving perpendicular to the field.

The electric potential in an electric field can also be determined in terms of the electric field strength and the distance:

$$V = \frac{\Delta U}{q} = \frac{W}{q} \text{ so, } W = Vq$$

Since $W = QEd$, substituting $W = Vq$ gives:

$$Vq = qEd \text{ and } V = Ed$$

Worked example 5.3.2

WORK DONE ON A CHARGE IN A UNIFORM ELECTRIC FIELD

Isabelle sets up a parallel plate arrangement so that one plate is at a potential of 12.0 V and the other earthed plate is positioned 0.50 m away. Calculate the work done to move a proton from the positive plate a distance of 10.0 cm towards the negative plate. ($q_p = +1.60 \times 10^{-19}$ C)

Identify what does the work and what the work is done on.

Thinking	Working
Identify the variables presented in the problem to calculate the electric field strength E.	$V_2 = 12.0\,\text{V}$ $V_1 = 0\,\text{V}$ $d = 0.50\,\text{m}$ $q = 1.60 \times 10^{-19}\,\text{C}$
Derive the equation $V = Ed$ and use it to calculate the value of E.	$V = \frac{\Delta U}{q} = \frac{W}{q}$ so, $W = Vq$ $W = qEd$, substituting $W = Vq$ gives: $Vq = qEd$ and $V = Ed$ $E = \frac{V}{d}$ $= \frac{12.0 - 0}{0.50}$ $= 24.0\,\text{V m}^{-1}$
Use the derived equation $W = qEd$ to determine the work done. Note that d here is the distance that the proton moves.	$W = qEd$ $= (1.60 \times 10^{-19}) \times 24.0 \times 0.100$ $= 3.8 \times 10^{-19}\,\text{J}$
Determine if work is done on the charge by the field or if work is done on the field.	As the positively charged proton is moving naturally towards the negative plate, then work is done on the proton by the field.

➤ Try yourself 5.3.2

WORK DONE ON A CHARGE IN A UNIFORM ELECTRIC FIELD

Jack sets up a parallel plate arrangement so that one plate is at a potential of 36.0 V and the other earthed plate is positioned 2.00 m away. Calculate the work done to move an electron from the positive plate a distance of 75.0 cm towards the negative plate. ($q_e = -1.60 \times 10^{-19}$ C)

Identify what does the work and what the work is done on.

COMPARING GRAVITATIONAL AND ELECTRIC FIELDS

Gravitational force brings gas clouds together to form planets, stars and galaxies. It causes stars to collapse to black holes, generating gravitational fields strong enough that even light can't escape. Yet the gravitational force of attraction between two electrons is less than 8×10^{-37} N.

The relationships developed for gravitational and electric fields over this chapter and Chapter 4 reveal the parallels and differences between related field concepts for gravitational masses and point charges. They are summarised in Table 5.3.1. Note that, in some instances, the equations in this table have been transposed to make the comparable quantity the subject.

TABLE 5.3.1 Comparison of gravitational and electric fields

Quantity or description	Gravitational fields	Electrical fields
how field strength varies with distance, *r*, from a mass or charge	$g = \frac{GM}{r^2}$	$E = \frac{kq}{r^2}$
force between masses or charges	$F = \frac{GMm}{r^2}$	$F = \frac{kQq}{r^2}$
potential energy changes in a uniform field	$\Delta E_p = mg\Delta h$	$\Delta U = Vq$
force due to a uniform field	$F_g = mg$	$F = qE$

5.3 Review

SUMMARY

- Electric field strength can be expressed as $E = \frac{F}{q}$ and $E = \frac{V}{d}$.
- Between two oppositely charged parallel plates, the field lines are parallel and therefore the field has uniform strength.
- When charges are in an electric field, they accelerate in the direction of the force acting on them.
- Electrical potential energy is the energy that is stored in an electric field when a charge is placed somewhere in that field.
- Electrical potential energy allows work to be done on a charged particle in a field.
- When a charged object is moved against the direction it would naturally move in an electric field, then work is done on the field.
- When a charged object is moved in the direction it would naturally tend to move in an electric field, then the field does work on the particle.
- Recall from *Pearson Physics Queensland Units 1 & 2* that electric potential is defined as the work required per unit charge to move a positive point charge from a reference point to a place in the electric field, $V = \frac{W}{q} = \frac{\Delta U}{q}$.
- By defining the reference point as infinity and setting the electric potential at this point to zero, the change in electrical potential energy is equal to the work done, *W*.
- The work done on or by an electric field can be calculated using the equations $W = qV$ or $W = qEd$.
- Potential difference is the change in potential energy when an electric charge is moved in an electric field.

5.3 Review *continued*

KEY QUESTIONS

Describe

1 Describe electric potential.

2 Describe electrical potential energy.

3 Describe potential difference in terms of electric fields.

Apply

4 Describe a situation in which work is done by a field on a charge, as well as one in which work is done by a charge on a field.

5 Determine if work was done on the field or by the field, or if no work is done, for each of the following charged objects in a uniform electric field.

- **a** An electron moves towards a positive plate.
- **b** A positively charged point remains stationary.
- **c** A proton moves towards a positive plate.
- **d** A lithium ion (Li+) moves parallel to the plates.
- **e** An alpha particle moves away from the negative plate.
- **f** A positron moves away from the positive plate.

6 A charge of +2.0 C moves from one point, X, to another point, Y, within an electric field. The potential energy deceases by 18 J. Deduce the point of highest electric potential.

7 A small positive charge, q, is moved a distance, d, toward a larger charge, Q, determine how far a charge of $2q$ should be moved in order to pass through the same potential difference. Give your answer in terms of the distance d.

8 If the voltage between two test points is measured as zero, determine the net (total) work done on a charge that is moved between the two points.

Analyse

9 Calculate the work done when a charge of 3.50 C is moved through a potential difference of 12 V.

10 An alpha particle is located in a parallel plate arrangement that has a uniform electric field of $34.0\,\mathrm{V\,m^{-1}}$.

- **a** Calculate the work done to move the alpha particle a distance of 1.00 cm from the earthed plate to the plate with a positive potential. ($q_a = +3.204 \times 10^{-19}\,\mathrm{C}$)
- **b** Determine whether work was done on the field by the alpha particle, by the field on the particle or if no work was done.

11 Calculate the potential difference that exists between two points separated by 45.0 cm and parallel to the field lines in an electric field of strength $6.7 \times 10^{2}\,\mathrm{V\,m^{-1}}$.

12 Calculate the potential difference that exists between two points separated by 30.0 cm, parallel to the field lines, in an electric field of strength $4.00 \times 10^{3}\,\mathrm{V\,m^{-1}}$.

Chapter review

05

KEY TERMS

Coulomb's law
electric field
electric field strength
electrical potential energy
electric potential
electrostatic force
field lines
point charge
potential difference

KEY QUESTIONS

Describe

1 Select the best option that describes an electric field.

A a region around an object that causes a force on other objects within that region

B a region around a charged object that causes a charge on other objects within that region

C a region around a charged object that causes a force on other objects within that region

D a region around a charged object that causes a force on other charged objects in that region

2 The direction of an electric field is best described as:

A towards a positively charged object

B away from a neutrally charged object

C away from a positively charged object

D away from a negatively charged object

3 Identify where the electrical field strength will be at a maximum between two plates forming a uniform electric field.

A close to the positive plate

B close to the earthed plate

C at all points between the plates

D at the mid-point between the plates

4 Identify the relationship between work done and potential difference by selecting the correct italicised terms to complete the sentence.

When a positively charged particle moves across a potential difference from a positive plate towards an earthed plate, work is done by the *field / charged particle* on the *field / charged particle*.

Apply

5 Explain the difference between electric potential and potential difference.

6 A charge of $+q$ is placed a distance r from another charge also of $+q$. A repulsive force of magnitude F is found to exist between them.

Describe the changes, if any, which will occur to the force in the following situations, by choosing the correct italicised terms.

a The distance between the charges is doubled to $2r$, so the force will *halve / double / quadruple / quarter* and *repel / attract*

b The distance between the charges is halved to $0.5r$, so the force will *halve / double / quadruple / quarter* and *repel / attract*

c The distance between the charges is doubled and one of the charges is changed to $-2q$, so the force will *halve / double / quadruple / quarter* and *repel / attract*

Analyse

7 A test charge is placed at a point, P, 30 cm directly above a charge, q, of $+30 \times 10^{-6}$ C. Determine the magnitude and direction of the electric field at point P.

A $300\,\text{N}\,\text{C}^{-1}$ upwards

B $300\,\text{N}\,\text{C}^{-1}$ downwards

C $3 \times 10^{6}\,\text{N}\,\text{C}^{-1}$ upwards

D $3 \times 10^{6}\,\text{N}\,\text{C}^{-1}$ downwards

The following information relates to questions **8–11**.

Two insulated spheres, X and Y, are set a distance d apart from each other. Both spheres have the same charge of $+q$. The force that each of the spheres exerts on the other is 4.0×10^{-5} N.

Use the following key to indicate the effect on the magnitude of the force between the two spheres when each of the changes in questions **8–11** is made.

A The force is reduced to one quarter of the original.

B The force remains unchanged.

C The force is doubled.

D The force is increased to four times the original.

8 An additional charge of $+3q$ is added to the charge on sphere X.

9 The distance between spheres X and Y is doubled.

10 A additional charge of $-2q$ is added to the charge on sphere Y.

11 The distance between spheres X and Y is now decreased to $\frac{d}{3}$ and the charges on spheres X and Y are changed to $+0.2q$ and $+5q$ respectively. Calculate the magnitude of the new force between the charges.

12 Calculate the force applied to an oil drop carrying a charge of 3.00 mC in a uniform electric field of $7.50\,\text{N}\,\text{C}^{-1}$.

13 Calculate the potential difference that exists between two points separated by 25.0 mm and parallel to the field lines in an electric field of strength $1.00 \times 10^3\,\text{V m}^{-1}$.

14 Calculate the magnitude of the force that would exist between two 1.00 C point charges separated by 1.00 km.

15 At a point near a charged surface, a charge of 2 μC experiences an electric force of 6 μN west. Identify the electric field strength at this point?

A $3\,\text{N C}^{-1}$ west
B $3\,\text{N C}^{-1}$ east
C $3\,\mu\text{N C}^{-1}$ west
D $12\,\mu\text{N C}^{-1}$ west

16 Brushing your hair can create a static charge. Assuming the electric field strength at a particular point near your hair is $75\,\text{N C}^{-1}$ east. If a dust particle with a charge of -8.0×10^{-18} C arrives at the same point, calculate the electric force acting on the dust particle.

17 At a particular point in a fluorescent tube, the electric field strength is $28\,\text{N C}^{-1}$ south. A mercury ion within the tube at this same point, experiences an electric force of 8.0×10^{-18} N south. Calculate the charge on the mercury ion.

18 Earth carries a net charge of -6.0×10^5 C. The electric field strength at a distance *r* from the centre of the Earth has a magnitude of $120\,\text{N C}^{-1}$. Determine the distance, *r*.

19 A particular electron gun accelerates an electron across a potential difference of 15 kV, a distance of 12 cm between a pair of charged plates. Determine the magnitude of the force acting on the electron. Use $q_e = 1.60 \times 10^{-19}$ C.

20 The positive and negative terminals of a watch battery have 20 nJ and 2 nJ of electrical potential energy respectively. Calculate the electrical potential difference between the two terminals if the positive terminal has a charge of 2.0 nC.

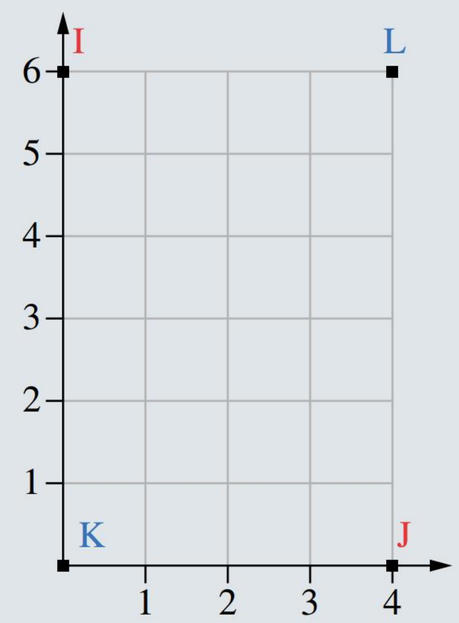
21 An electroscope is charged with an electric potential of 500 V. Determine the electrical potential that a charge of +13 pC would have when on the electroscope.

22 Calculate the magnitude of the force that would exist between two point charges of 5.00 mC and 4.00 nC separated by 2.00 m.

23 A point charge of 2.25 mC is positioned on top of an insulated rod on a table. Calculate the distance above the point charge at which a sphere of mass 3.00 kg containing a charge of 3.05 mC should be located so that it is suspended in the air.

24 Two point charges (30.0 cm apart in air) are charged by transferring electrons from one point to the other. Calculate how many electrons must be transferred so that an attractive force of 1.0 N exists. Consider only the magnitude of q_e in your calculations.

25 Two positive and two negative charges are fixed on the edges of a 4.0 mm × 6.0 mm table as shown below: Point I has a charge of $+2.0_e$ (elementary charges), L has a charge of -4.0_e, K has a charge of -3.0_e, and J has a charge of $+5.0_e$.
Calculate the net force (magnitude and direction) acting on charge I.



26 A charged plastic ball of mass 5.00 g is placed in a uniform electric field pointing vertically upwards with strength of $300.0\,\text{N C}^{-1}$. Calculate the magnitude and sign of the charge required on the ball to create a force upwards that exactly equals the weight force of the ball.

27 Two metal spheres, one carrying a charge of −16.0 mC and the other a charge of +5.00 mC, are attracted to each other and touch. The charge distributes so the charge is equal on each sphere. A force of repulsion then exists between them and they move apart.

a Calculate the force of attraction between them when they are 2.00 mm apart before they touch.
b Determine the charge on each sphere after they touch.
c Calculate the force between them after they touch and move 6.75 mm apart.

28 A beam of electrons, initially at rest, is accelerated in the electron gun of a linear accelerator to a velocity of $5.30 \times 10^7\,\text{m s}^{-1}$.

a Calculate how much work is done on each electron to achieve this velocity.
b Determine the voltage they are accelerated through.

29 Two electrons approach each other. The charge on each electron is -1.60×10^{-19} C. Determine the electrical force of repulsion between the two electrons when they are 5.4×10^{-12} m apart.

Interpret

30 Zhoufan and Sylvia are experimenting with an unknown ion and wish to determine the charge that it carries. They only have equipment sensitive enough to compare ratios between relative forces (for example, force A is three times stronger than force B). The distance between any two charges can be reliably measured.

To determine the charge on the unknown ion, they set up an experiment in which a maximum of two electrons and two ions can be laid down.

Design a setup for this experiment that will allow them to determine the charge on the ion, and explain why such a setup is necessary.

31 A researcher sees a negatively charged oil drop with a mass of 1.161×10^{-14} kg hover stationary between two horizontal parallel plates. Between the plates there is an electric field of strength $3.55 \times 10^{4}\,\mathrm{N\,C^{-1}}$. The field is pointing vertically downwards.

Determine how many extra electrons are present in the oil drop. ($q_e = -1.60 \times 10^{-19}$ C and $g = 9.8\,\mathrm{N\,kg^{-1}}$)

Data analysis

DATA SET 1

The information below applies to Questions **1**–**3**.

An experiment was conducted to experimentally investigate the relationship between the force of attraction between two charged spheres and the distance between them. The charge on each sphere was kept constant while the distance between the two spheres was decreased. Three trials were measured for each distance. The absolute uncertainty in the measurement of the distance between the spheres was ±0.005 m.

The raw data from this experiment is shown in Table 1 and plotted data in Figure 1.

TABLE 1 Raw data: force versus distance

Distance (m)	Force trial 1 (N)	Force trial 2 (N)	Force trial 3 (N)	Avg. force (N) ±
0.20	20.1	19.9	20.0	20.0 ± 0.10
0.14	37.1	37.1	36.9	37.0 ± 0.10
0.10	62.2	61.9	62.0	62.0 ± 0.15
0.09	88.9	88.9	89.2	62.0 ± 0.15
0.08	120.2	120.3	119.8	120.1 ± 0.25
0.07	149.7	150.0	150.3	150.0 ± 0.30
0.06	190.5	190.8	191.6	191.0 ± 0.55
0.05	240.4	241.1	241.5	±

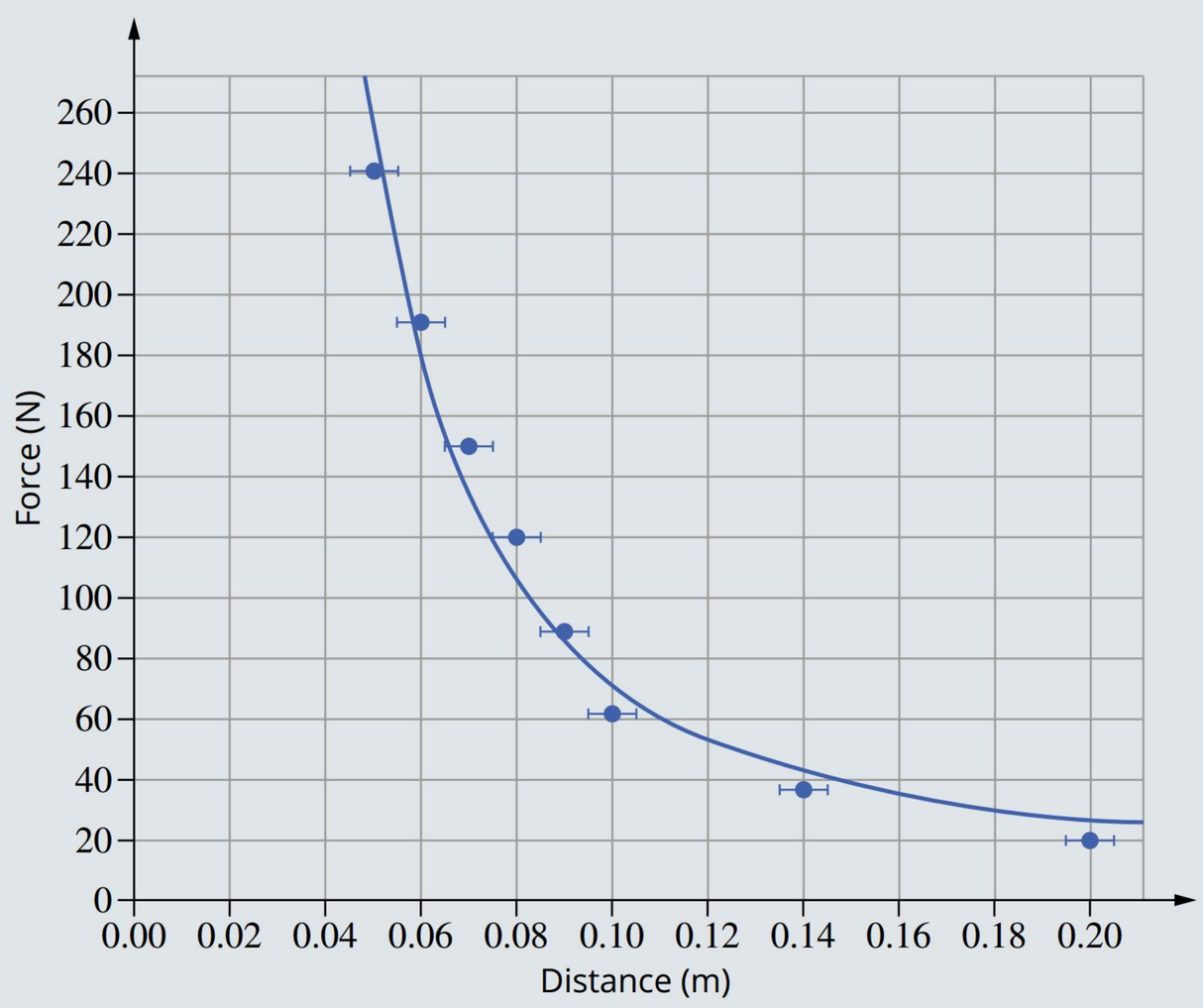


FIGURE 1 Graph of force versus distance

Question 1 (1 mark)

Calculate the average for the final trial

Question 2 (1 mark)

Determine the absolute uncertainty for the final trial using the formula $\Delta\bar{x} = \pm\frac{(x_{max} - x_{min})}{2}$

Question 3 (2 marks)

Identify the relationship between the Force (F) and the distance (r) between the two charged spheres. Use evidence from the graph to support your answer.

CHAPTER 06

Magnetic fields

In 1820, Hans Christian Oersted discovered that an electric current could produce a magnetic field. His work established the initial ideas behind electromagnetism. Since then, our understanding and application of electromagnetism has developed to the extent that much of our modern way of living relies upon it. For example, with the use of the electric motors and generators which revolutionised the way energy is utilised in our society. Particle accelerators, which are used for a variety of applications including medical research, also heavily rely on the concepts discussed here.

In this chapter you will investigate the concept of magnetism, how to describe magnetic fields through the use of field diagrams, how to solve problems relating to magnetic field strength and force in different scenarios including through interpreting experimental data.

Syllabus subject matter

MAGNETIC FIELDS

- Describe the concept of a magnetic field. **6.1, 6.2**
- Sketch magnetic field lines due to a moving electric charge, electric currents and magnets. **6.2, 6.3**
- Describe the generation of a magnetic field from a moving electric charge. **6.3**
- Solve problems involving the magnitude and direction of magnetic fields around a straight electric current-carrying wire and inside a solenoid using $B = \frac{\mu_0 I}{2\pi r}$ and $B = \mu_0 n I$. **6.3**
- Describe the force experienced by electric current-carrying conductors and moving electric charges when placed in a magnetic field. **6.4, 6.5**
- Solve problems involving the magnetic force on an electric current-carrying wire and moving charge in a magnetic field using $F = BIL\sin\theta$ and $F = qvB\sin\theta$ **6.4, 6.5**
- Interpret data relating to the force acting on a conductor in a magnetic field. **6.4**
- Interpret data relating to the strength of a magnet at various distances. **6.1, 6.3**

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6.1 Magnetic fields

BY THE END THIS MODULE, YOU SHOULD BE ABLE TO:

- describe a magnetic field
- describe the types of objects that produce magnetic fields
- interpret data relating to the strength of a magnet at various distances.

FIGURE 6.1.1 In 1820, Hans Christian Oersted discovered the magnetic effect created by an electric current. Oersted is honoured by this statue in Oersted's Park, Copenhagen.

Although naturally-occurring magnets had been known about for many centuries, by the early 19th century there was still no scientifically proven way of creating an artificial magnet. In 1820, the Danish physicist Hans Christian Oersted (whose statue is shown in Figure 6.1.1) developed a scientific explanation for the magnetic effect created by an electric current.

Oersted noticed that when he switched on a current from a simple battery, a magnetic compass nearby moved (see *Pearson Physics Queensland Units 1 & 2*). Intrigued by this observation, he carried out further experiments, which demonstrated that it was the current from the battery that was affecting the compass movement. His experiments showed that the stronger the current, and the closer the compass was to it, the greater the observed effect. These observations led him to conclude that the electric current was creating a **magnetic field**. This connection between electric and magnetic fields is fundamental to society today.

MAGNETISM

Before looking further into the connection between electric current and magnetic fields, it is necessary to review some fundamentals of **magnetism**. Magnetism is a physical phenomenon caused by magnets that results in a field that attracts or repels other magnetic materials.

The magnetic effect most people are familiar with is the attraction of iron or other **magnetic** materials to a magnet (Figure 6.1.2).

FIGURE 6.1.2 A bar magnet attracts drawing pins.

If you experiment with a magnet, you will find that each end of a magnet behaves differently, particularly when interacting with another magnet. One end will be attracted while the other is repelled. Each end of a magnet is referred to as a **magnetic pole**.

Like magnetic poles repel each other; unlike magnetic poles attract each other. These effects of attraction or repulsion of magnets are referred to as the **magnetic force**.

TYPES OF MAGNETS

There are three types of magnets with which you may be familiar: permanent magnets, temporary magnets and electromagnets. **Permanent magnets** are materials that hold magnetic properties over a long period of time, or indefinitely. The magnets you keep on your refrigerator are permanent magnets. **Temporary magnets** are materials, such as soft iron, that will temporarily gain magnetic properties when exposed to a strong enough magnetic field. **Electromagnets**, which will be explored in more detail in Module 6.3, utilise magnetic fields produced by passing an electric current through a coil of wire.

Some materials experience magnetism more than other materials. For example, iron, cobalt and nickel experience magnetism more than aluminium. These materials are known as ferromagnetic materials. **Ferromagnetic materials** can easily be magnetised to become permanent magnets.

MAGNETIC FIELDS

In the previous chapter, you saw that point charges and charged objects produce an electric field in the space that surrounds them. For this reason, charged bodies within the field will experience a force. The direction of the electric field is determined by the direction of that force.

Magnets also create fields. If you do a simple test such as placing a pin near a magnet, you will observe that the pin will be pulled towards the magnet. This shows that the space around the magnet must therefore be affected by the magnet.

If you sprinkle iron filings on a piece of clear acetate that is held over a magnet, you will observe that the magnetic field will be clearly defined (Figure 6.1.3). The iron filings will line up with the field, showing clear field lines running from one end of the magnet to the other (Figure 6.1.3a). These field lines will be explored in a vector representation in Module 6.2.

Magnetic materials induce a magnetic field, and any other magnetic materials will interact with that field and experience a force. For example, if you were to hold two magnets close together with the north pole of one close to the south pole of the other, they would both induce a magnetic field and interact with each other's fields. The resulting force of attraction between the north and south poles is a consequence of the interaction with these fields. Similarly, when two like poles interact (for example, north and north) a force of repulsion will be experienced due to the interaction of the magnetic fields.

Strength of a magnetic field

As the distance from a magnet increases, the magnetic field is spread over a greater area and its strength at any point decreases. This relationship is therefore an inverse relationship. The exact relationship will be dependent on the size, shape and strength of the magnet. The relationship will also vary with distance, as when you are closer to the magnet, the distance between the poles is no longer negligible. Generally, bar magnets will follow an inverse cubed relationship.

To find this relationship for a given magnet, data can be collected and analysed. To do this a device such as a magnetometer or Gaussmeter is used (Figure 6.1.4). These are sensors that interact with magnetic fields and can quantify the strength of the field at a given point. You can also often find a magnetometer app on a smartphone to collect this sort of data, which often gives the strength of the magnetic field in units of mT (milli Tesla, $\times 10^{-3}$ T) or μT (micro-Tesla, $\times 10^{-6}$ T).

FIGURE 6.1.4 A Gaussmeter can be used to collect data related to the strength of a magnetic field at a given point. Here the Gaussmeter reads 0.07 mT, equivalent to 0.07×10^{-3} T.

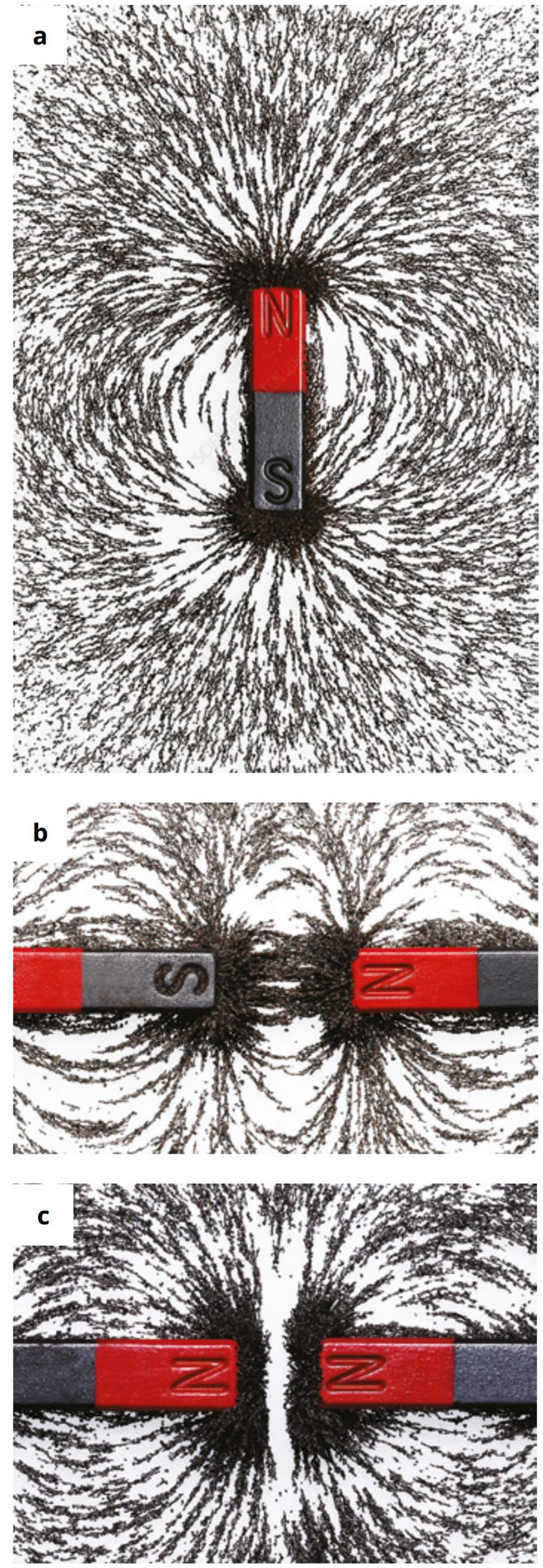
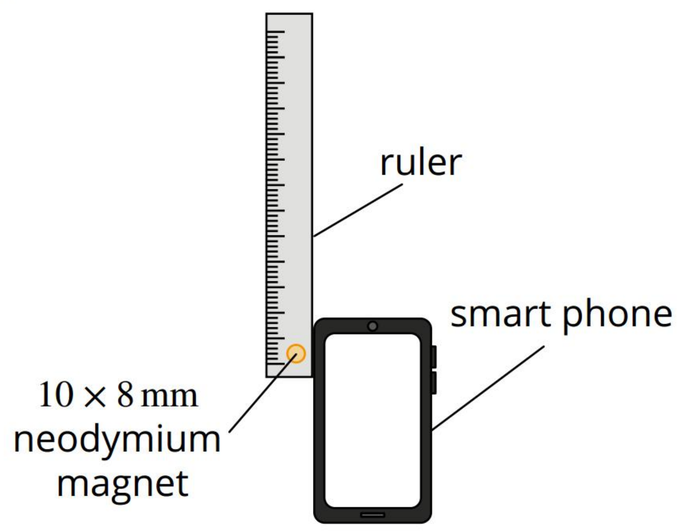


FIGURE 6.1.3 Iron fillings sprinkled around (a) a single bar magnet, and magnets with (b) unlike poles close together and (c) like poles close together. The patterns in the fields show the attraction and repulsion between poles.

Worked example 6.1.1

STRENGTH OF A MAGNETIC FIELD

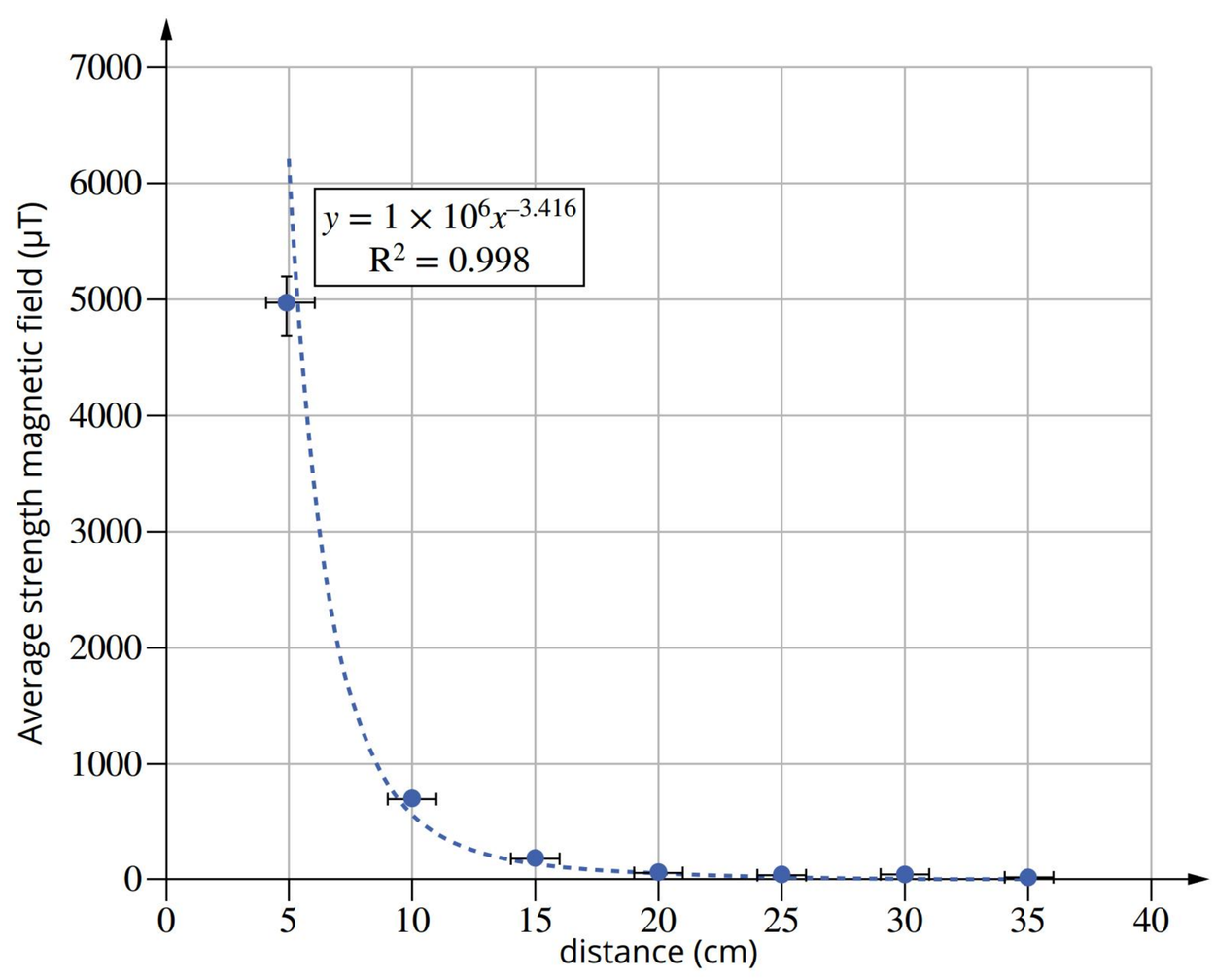
A student is testing the strength of a magnetic field around a magnet using a magnetometer app on their phone. They setup the experiment as in the following diagram.



After collecting three trials of data by moving the magnet along the rule to set distances, they averaged their results as shown in the table:

Distance, r (cm) ± 0.5 cm	Average strength magnetic field, B (μT)	ΔB (μT)
5	4952	243
10	689	22
15	163	4
20	58	3
25	25	2
30	12	2
35	7	1

a Create a graph of the data relating to the strength of a magnet at various distances.

Thinking	Working
Setup your axes with distance along the x-axis as the independent variable, and magnetic field strength on the y-axis as the dependent variable. Plot each of the points given in the table of data. Adding a trendline will help you to answer part b. Include the uncertainty of Δr and ΔB. Note that the error for the distance is quite large as it is not known where the exact location of the magnetometer is within the phone.	

b Using the graph created in part a), interpret the relationship between distance from the magnet and the magnetic field strength.

Thinking	Working
Comment on the shape of the graph.	The relationship between distance and magnetic field strength for this magnet follows an inverse power relationship, where $$B \propto \frac{1}{r^{3.416}}$$

c Linearise the data and analyse the relationship.

Calculate the values for $\frac{1}{r^{3.416}}$,

Note that the relationship found in part b is an approximation. Often for magnets, the power relationship can be complex and vary with distance. You can assume that the magnet follows the same power relationship at each distance for the sake of simplicity.

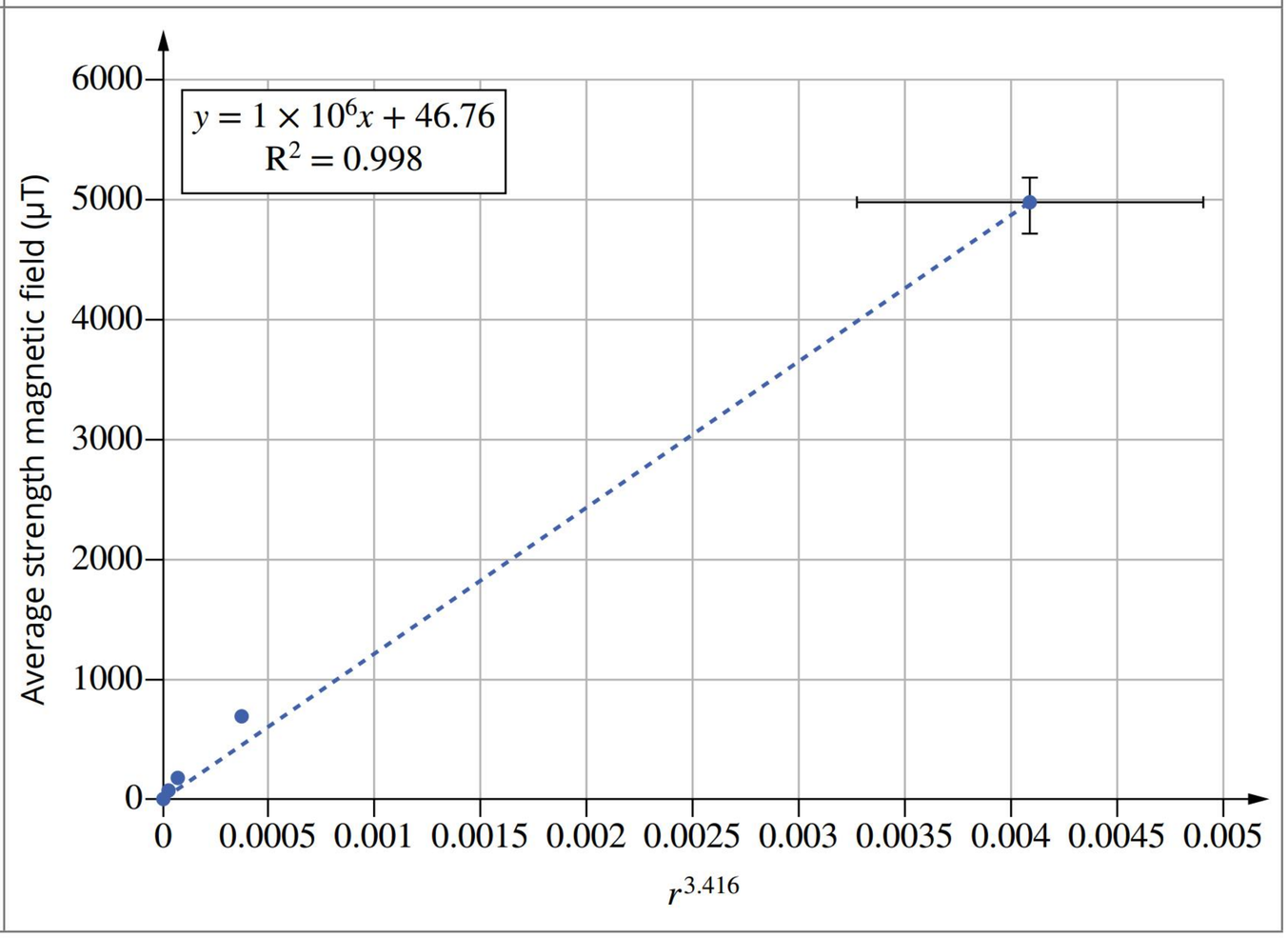
$\frac{1}{r^{3.416}}$ (cm)
4.0×10^{-3}
3.8×10^{-4}
9.6×10^{-5}
3.6×10^{-5}
1.7×10^{-5}
9.0×10^{-6}
5.3×10^{-6}

Calculate the percentage uncertainty for the distance values using

$$\frac{\Delta r}{r} \times 100\%$$

Δr (%)
20
10
6.7
5
4
3.3
2.9

Create a graph of the linearised data including the updated uncertainty values.

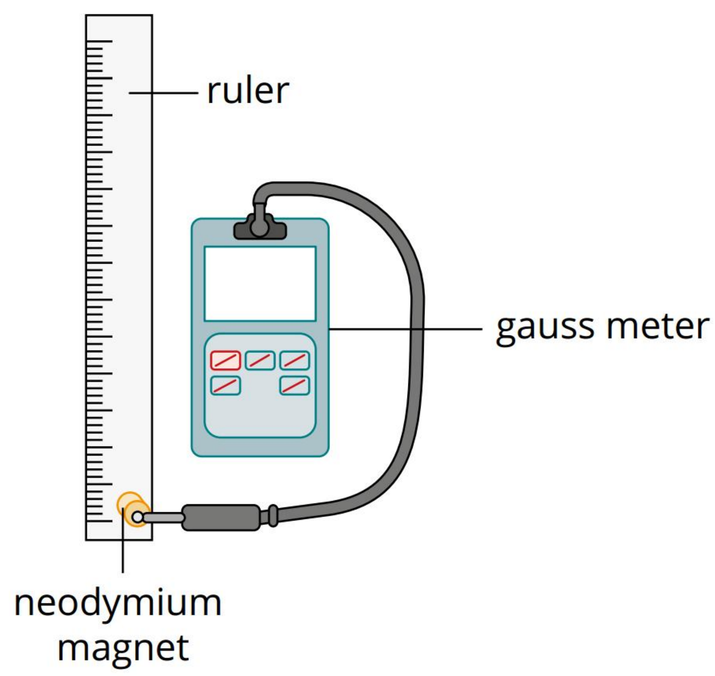


Analyse the relationship. As discussed, when close to the magnet the distance between the poles is no longer negligible and this interaction will alter the relationship. This appears to be affecting the derived relationship as it fits above and below certain data points.	The relationship is found to be $B = 1 \times 10^6 \frac{1}{r^{3.416}} + 46.76$ Where B is in μT and r is in cm. The relationship is close to an inverse cube relationship which is to be expected. Note the very high uncertainty in the distance for the value closest to the magnetometer. This is because the exact location of the magnetometer within the phone is unknown so the percentage uncertainty at small distances is large. Note also the y-intercept of approximately 47. This may be due to the Earth's background magnetic field or some other limiting error within the magnetometer itself. The R^2 value is reasonable for this experiment.

➤ Try yourself 6.1.1

STRENGTH OF A MAGNETIC FIELD

A student is testing the strength of a magnetic field around a magnet using a Gaussmeter. They setup the experiment as in the following diagram.



Distance, r (cm) ± 0.5 cm	Average strength magnetic field (mT)	ΔB (mT)
5	5.127	0.710
10	0.610	0.021
15	0.165	0.004
20	0.059	0.003
25	0.027	0.002
30	0.013	0.002
35	0.006	0.001

a Create a graph of the data relating to the strength of a magnet at various distances.

b Using the graph created in part a, interpret the relationship between distance from the magnet and the magnetic field strength.

c Linearise the data and create a new graph of the linearised data set.

COMPARING MAGNETIC AND ELECTRIC FIELDS

Try breaking a bar magnet in half. What you get is two smaller magnets, each with its own north and south poles. No matter how many times you break the magnet and how small the pieces are, each will be a separate little magnet with two poles. Because bar magnets and electromagnets always have two poles, they are said to be **dipolar** (Figure 6.1.5). This is similar to electric charges where a positive and negative charge in close proximity to each other are said to form a **dipole**.

When two charges form a dipole, unlike charges are attracted while like charges are repulsed. Similarly, for magnetic fields, two unlike poles are attracted while two like poles feel a repulsive force.

A key difference is that you cannot have a single magnetic pole (or monopole), whether it be a south pole or a north pole; however, charges *can* exist on their own as either a positive or negative charge. Magnetic fields do not currently have monopole sources, only dipoles. Electric fields, however, are induced by single electric charges. Theoretically, magnetic monopoles could exist in nature, but they have not been observed, although magnetic monopole behaviour has been observed in quasiparticles (particles that cannot exist outside of a system).

Like an electric field, a magnetic field decays the further you are away from its source. Unlike electric fields, however, magnetic fields do not have point sources—they must always be between a north and a south pole. As a result, the patterns of their field lines are more complicated than simple electric fields.

FIGURE 6.1.5 Magnets are always dipolar.

EARTH'S MAGNETIC FIELD

A suspended magnet that is free to move will always orientate itself in a north–south direction. That's essentially what the needle of a compass is—a freely suspended, small magnet. If allowed to swing vertically as well, then the magnet will tend to tilt vertically. The vertical direction (upwards/downwards) and the magnitude of the angle depend upon the direction of the magnet from either of the Earth's poles, and the magnet's latitude.

Earth itself can be shown to have a giant magnetic field around it (Figure 6.1.6).

Earth's magnetic field is thought to come from electrical currents in the molten iron in Earth's outer core. The exact mechanism by which this field comes about is incredibly complex; however, scientists have been able to model some of its features.

The names for the poles of a magnet derive from early observations of magnets orientating themselves with Earth's geographic poles. The magnets aligned themselves with Earth's magnetic field.

Initially, the end of the magnet pointing toward Earth's geographic north was denoted the north **pole** (short for north-seeking pole), and compasses are thus marked with this end as north. This meant that the actual magnetic North Pole of the Earth acted like the south pole of a simple bar magnet. It is now known that the geographic North Pole and the magnetic North Pole are slightly apart in distance. The same applies to the geographic South Pole and the magnetic South Pole, and the south-seeking pole of a magnet.

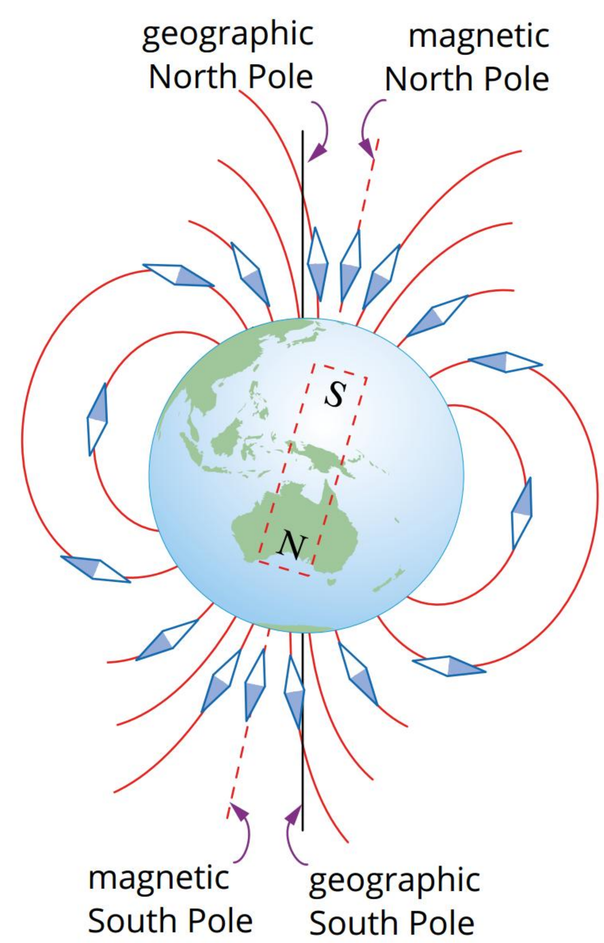


FIGURE 6.1.6 Earth acts somewhat like a huge bar magnet. The south pole of this imaginary magnet is near the geographic North Pole and is the point to which the north pole of a compass appears to point.

6.1 Review

SUMMARY

- Like magnetic poles repel, and unlike magnetic poles attract.
- Magnetic materials induce a magnetic field.
- Magnetic materials within a magnetic field will experience a force.
- Magnetic field lines can be observed running from one end of a magnet to the other.
- The strength of a magnet decreases as distance increases, so it follows an inverse relationship.
- Magnets are generally dipolar, having both north and south poles. A magnet, or a fundamental particle, with a single pole (monopole) is not known to exist.
- Earth has a dipolar magnetic field that acts like a huge bar magnet, with the south end near the geographic North Pole.

KEY QUESTIONS

Describe

1 Describe the force between two like magnetic poles.

2 Describe what is meant by saying a bar magnet is dipolar.

3 Identify a type of metal that can produce a magnetic field.

Apply

4 A magnetic material creates the magnetic field that, in turn, produces a magnetic force. This force is what causes magnetic materials to stick together, such as magnets to your refrigerator. Identify whether this force is a contact or non-contact force.

5 A magnet is suspended on a thin wire at its midpoint so that it is free to swing. Identify the approximate direction in which the north pole of the magnet will point, and explain your answer.

6 How does a compass detect the Earth's magnetic field?

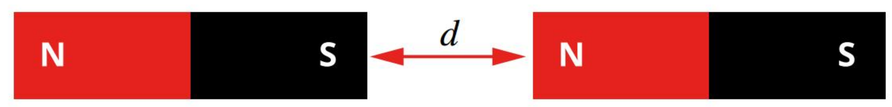
7 Compare electric and magnetic fields.

Analyse

8 Repeatedly cutting a bar magnet in half always produces magnets with two opposite poles. Determine the conclusion that can be reached in relation to the poles of a magnet, from this information.

9 Determine how you would test if an object was a magnet if you already had another magnet in your possession.

10 The following diagram shows two bar magnets separated by a distance *d*. At this separation, the magnitude of the magnetic force between the poles is equal to *F*.



a Describe generally what will happen to the force between the poles if the distance, *d*, is increased.

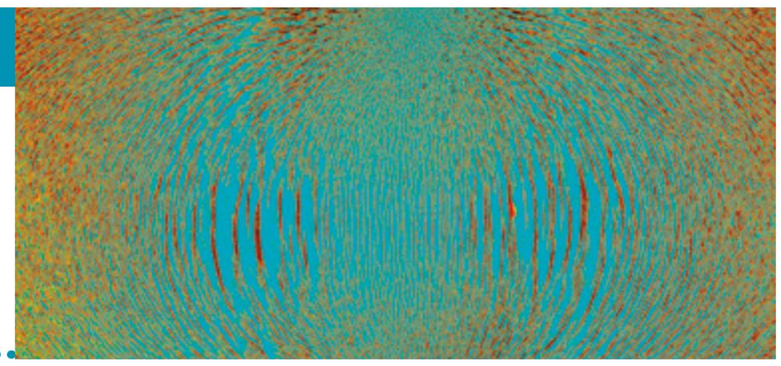
b Determine what happens to the resulting accelerating motion between the two poles if *d* is increased.

c Determine how acceleration and force between the magnets change if the magnets are allowed to move together.

6.2 Magnetic field diagrams

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- recall how to represent magnetic field lines
- sketch magnetic fields surrounding objects in different scenarios
- draw field lines to represent the magnetic fields of various systems
- relate magnetic field lines to your prior knowledge of vector diagrams.



In physics, abstract quantities are often represented using diagrams. Just as diagrams can illustrate the strength and direction of an electric field at various points in space, magnetic fields can also be depicted pictorially. Generally, magnetic field diagrams convey the magnitude of the force that a magnetic material would experience in a given region of space.

VECTOR FIELD MODEL FOR MAGNETIC FIELDS

Figure 6.2.1 shows the magnetic field associated with a simple bar magnet. The magnetic field around the bar magnet can be defined in vector terms by specifying both direction and magnitude.

The direction of the magnetic field at any point is the direction in which a compass would point if placed at that point, that is, towards the magnet's south pole. This is also the direction of the force the magnetic field would exert on an (imaginary) single north pole.

Denser (closer) lines indicate a relatively stronger magnetic field. As the distance from the magnet increases, the magnetic field is spread over a greater area and its strength at any point decreases. The strength and direction associated with the magnetic field at any point signifies that it is a vector quantity. The strength, or vector magnitude, of the magnetic field at a particular point is denoted by B and has units of tesla (T).

The field between two magnets is dependent on whether like or unlike poles are close together, the distance between the poles, and the relative strength of the magnetic field of each magnet. Iron filings or small plotting compasses can be used to visualise the field between and around the magnets (Figure 6.2.2).

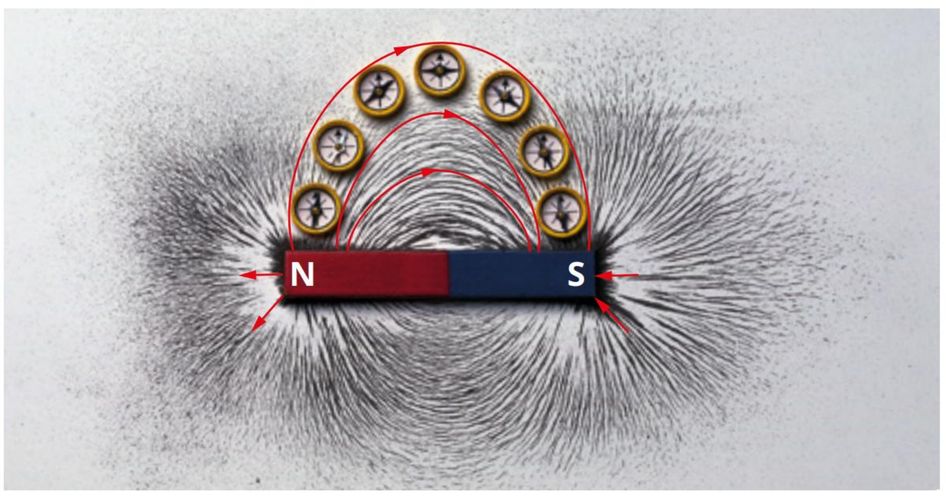


FIGURE 6.2.2 Field lines around a bar magnet can be visualised by placing small plotting compasses around the magnet. Field lines are drawn linking the direction in which each compass points, creating field lines that run from the north pole to the south pole of the magnet.

Because Earth has a giant magnetic field around it, you can also predict how compasses will orientate themselves around it; they will orientate themselves along the **magnetic field lines**. In Figure 6.2.2, note the direction of the magnetic field close to either pole, where the magnetic field lines run almost vertically. Magnets placed near Earth's magnetic poles will behave in the same way.

Different shaped magnets produce different shaped fields. Figure 6.2.3 shows the magnetic field plotted for a horseshoe magnet.

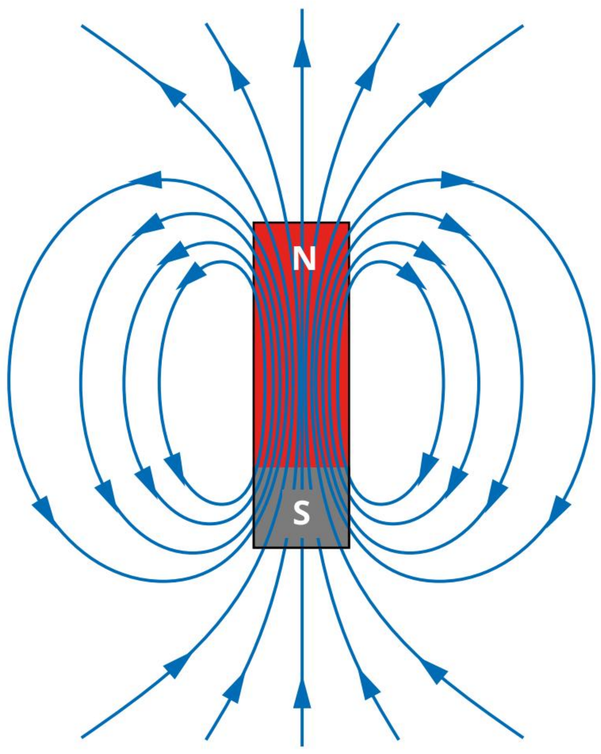


FIGURE 6.2.1 The field lines around and inside a bar magnet show the direction of the force on an (imaginary) single north pole.

The magnetic field is a vector quantity, as it has both a magnitude and a direction.
The strength, or vector magnitude, of the magnetic field is in units of tesla (T) and is denoted by the symbol B.

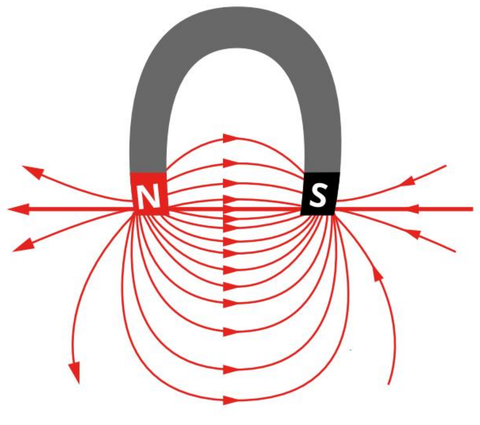


FIGURE 6.2.3 The horseshoe magnet has two unlike poles close to each other. This creates a very strong magnetic field between the poles.

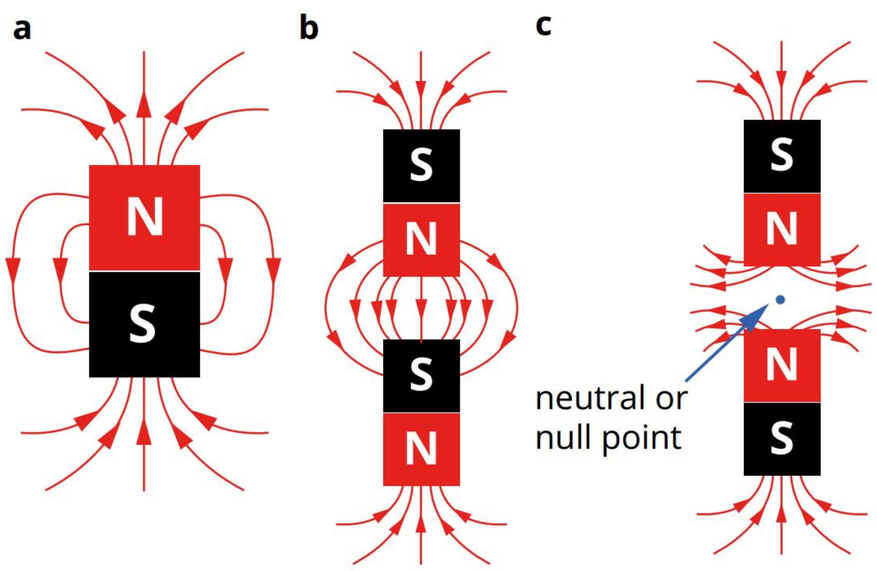


FIGURE 6.2.4 Magnetic field lines plotted for (a) a bar magnet, (b) opposite poles of magnets in close proximity and (c) like poles of magnets in close proximity.

The resultant direction of the magnetic field at a particular point will be the vector addition of each individual magnetic field acting at that point.

When two magnets are placed close together, two situations may arise. If the poles are unlike (Figure 6.2.4b), then attraction will occur between them, and a magnetic field will be created that extends between the two poles. If poles are alike (Figure 6.2.4c), repulsion will occur. In this situation, there will be a neutral point between the two poles where there is no magnetic field.

As the bar magnets in Figure 6.2.4 have a fixed strength and position, the associated magnetic fields will be static. Varying the magnetic field strength, by changing the magnets or varying the relative position of the magnets, would produce a changing magnetic field.

6.2 Review

SUMMARY

- The direction of a magnetic field at a particular point is the same as that of the force on an imaginary single north pole.
- The magnetic field is a vector quantity, as it has both magnitude and direction. The magnitude of a magnetic field is measured in tesla (T).
- The resultant direction of interacting magnetic fields at any particular point will be the vector addition of each individual magnetic field acting at that point.

KEY QUESTIONS

Describe

1 Describe the meaning of the direction of a magnetic field line at a particular point in space.

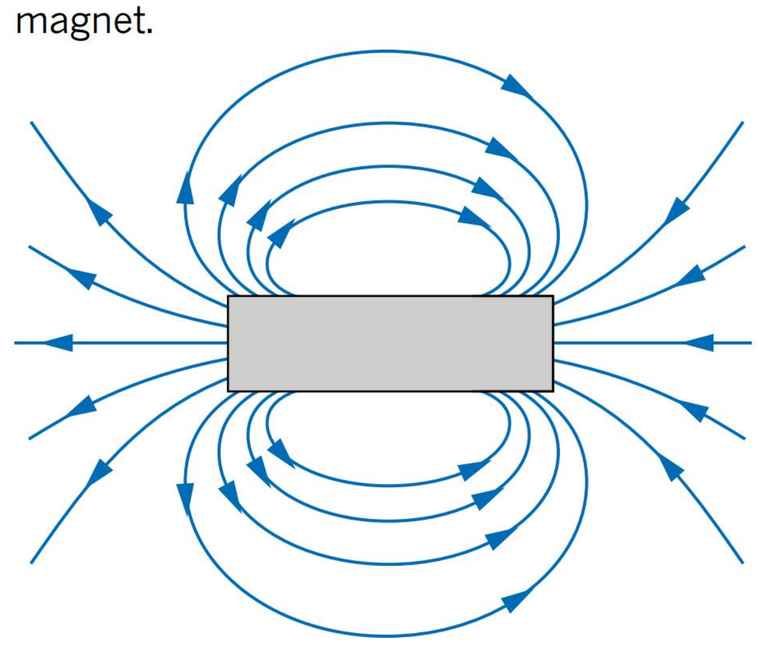
2 Sketch the magnetic field around a single bar magnet and indicate clearly the direction of the field and the location of the north and south poles.

3 Sketch the magnetic field lines around a horseshoe magnet and indicate clearly the direction of the field and the location of the north and south poles.

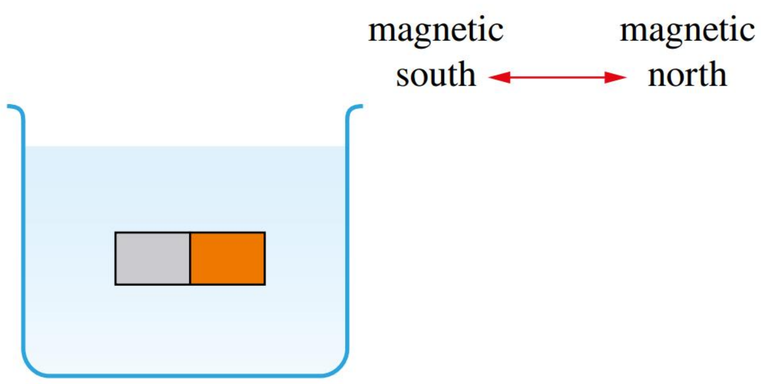
4 Describe how the strength of a magnetic field is indicated by the way field lines are drawn.

Apply

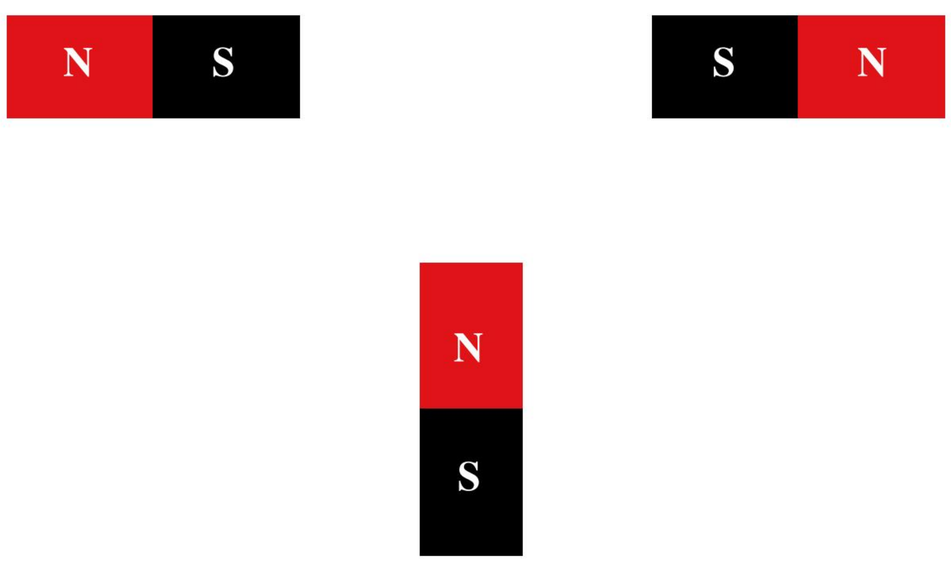
5 Label the north and south ends of the following bar magnet.



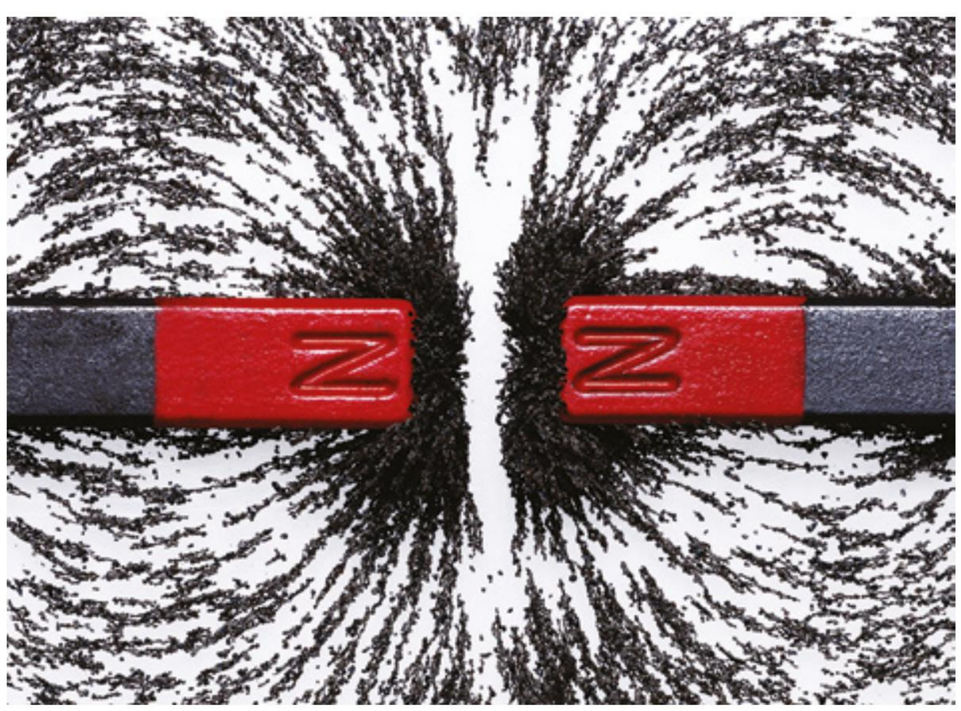
6 A student performs an experiment to test the properties of a bar magnet by observing how it aligns itself in Earth's magnetic field. She places the bar magnet in a container of water, and the magnet orientates itself according to the diagram below. Draw the field lines through the magnet and indicate its north and south poles.



7 Sketch the magnetic field lines around these three bar magnets.



8 Identify an area where the field is strongest and where it is comparatively weak in the following diagram. Justify your answer.

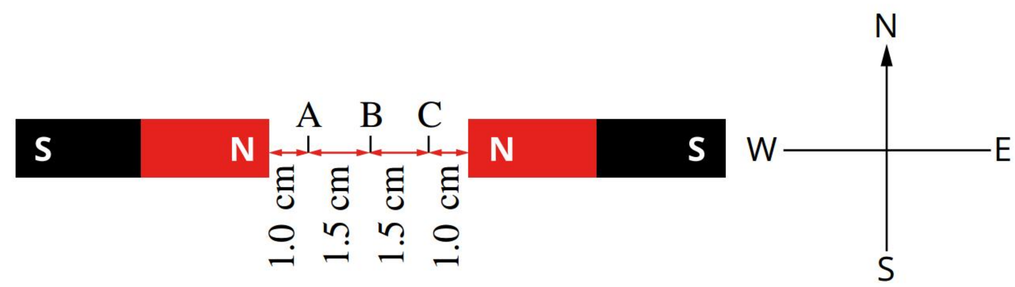


9 Explain how you could use a magnetometer to sketch a magnetic field diagram.

Analyse

The following information applies to questions **10–11**.

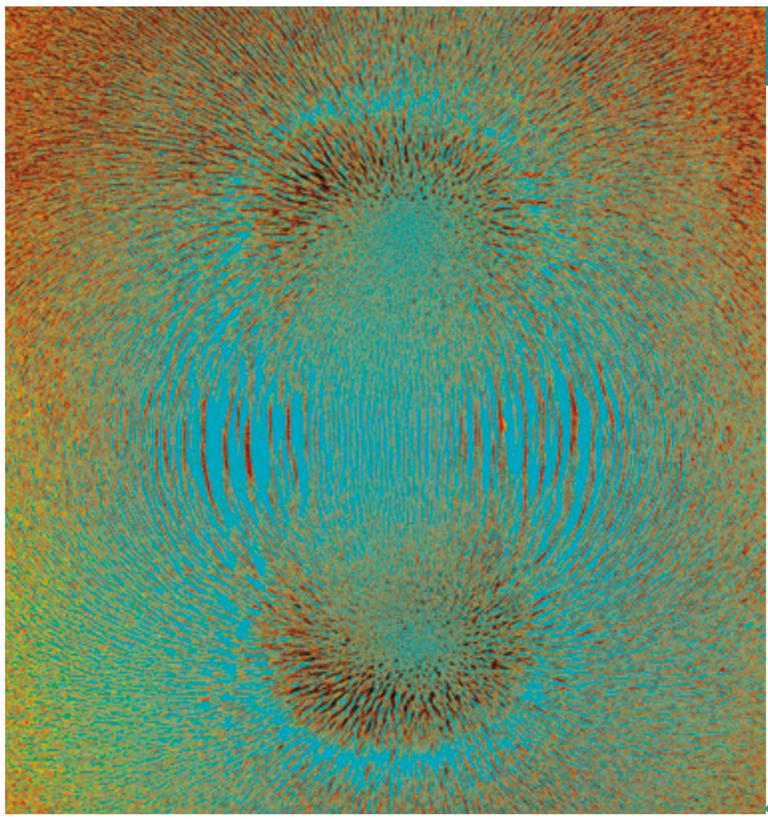
Two strong bar magnets which produce magnetic fields of equal strength are arranged as shown.



10 Contrast the approximate direction of the resulting magnetic field at points A and C, ignoring the magnetic field of Earth.

11 Predict the magnitude of the resulting magnetic field at point B, ignoring the magnetic field of Earth.

6.3 Creating magnetic fields



BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- describe how electric current can produce a magnetic field
- sketch magnetic field lines due to electric currents
- calculate the strength and direction of a magnetic field produced by a current-carrying wire
- understand the relationship between distance, current and the strength of a magnetic field
- interpret data relating to the strength of a magnet at various distances
- determine the magnitude and direction of magnetic fields inside different solenoids
- relate current-carrying coils to conventional bar magnets
- understand the relationship between the number of loops in a solenoid and its resulting magnetic field.

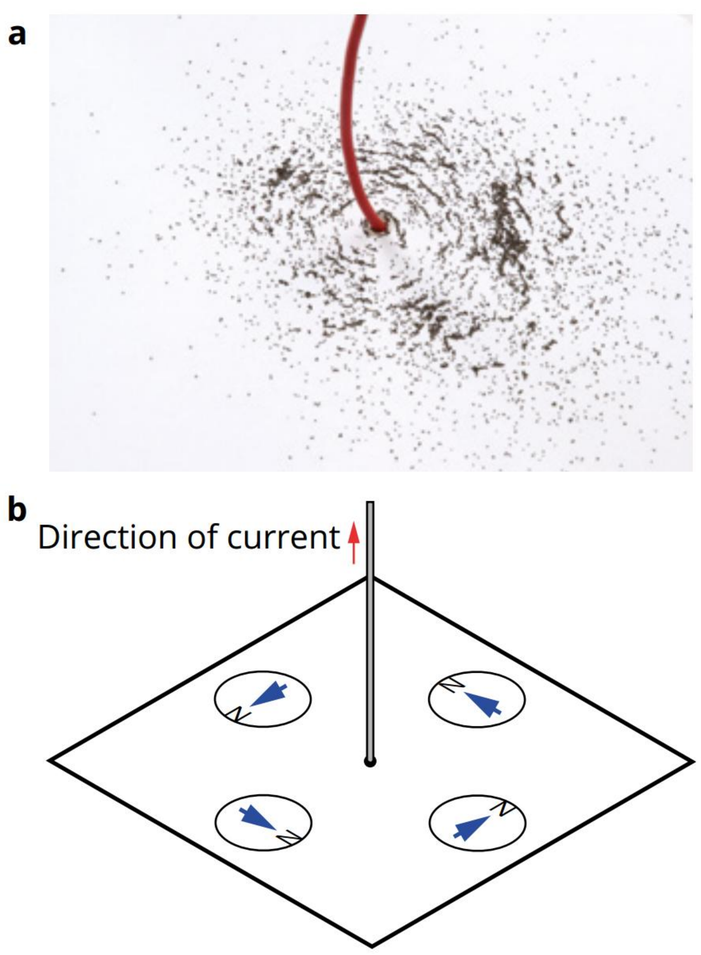


FIGURE 6.3.1 (a) The iron filings align with the magnetic field around a current-carrying wire and show the circular nature of the magnetic field. (b) Compasses indicate the direction of the field.

In general, magnetism arises from the movement of charged particles. This connection highlights the relationship between magnetic and electric fields: charged particles generate an electric field, and only through their motion does an induced magnetic field emerge. As established in electronics, current is the flow of charge, meaning that current-carrying wires produce a magnetic field with a specific magnitude and direction.

To make practical use of magnetic fields, it is essential to understand their behaviour and methods of generation. This section explores the creation of specific magnetic fields through various arrangements of wires and wire coils.

MAGNETIC FIELDS AND CURRENT-CARRYING WIRES

In the introduction to this chapter the discovery of the connection between electric current and magnetic fields was noted. Oersted found that when he switched on the current from a simple battery, a nearby magnetic compass would move.

A compass aligns itself at a tangent to the concentric circles around the wire (the magnetic field) so that the north-facing part of the compass points in the direction of the magnetic field (Figure 6.3.1). The stronger the current and the closer the compass is to the wire, the greater the force on the compass.

The magnetic field is perpendicular to the current-carrying wire, and the direction of the field will depend upon the current direction. There is a simple and easy way to determine the direction of the circular magnetic field, which is commonly referred to as the **right-hand grip rule**.

If safe, grasp the conducting wire with your right hand with your thumb pointing in the direction of the conventional electric current, I (positive to negative). (If it is not safe, imagine grasping the wire.) Observe the way your fingers are curled around the wire. The circular magnetic field will be perpendicular to the wire and in the direction your fingers are pointing (Figure 6.3.2).

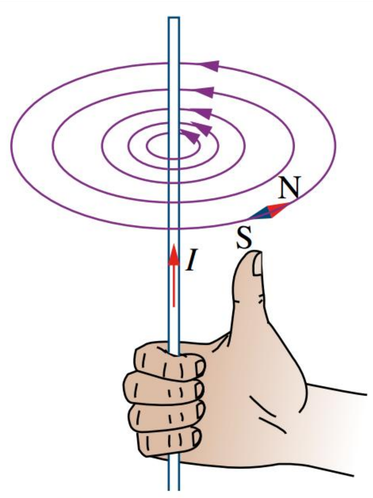
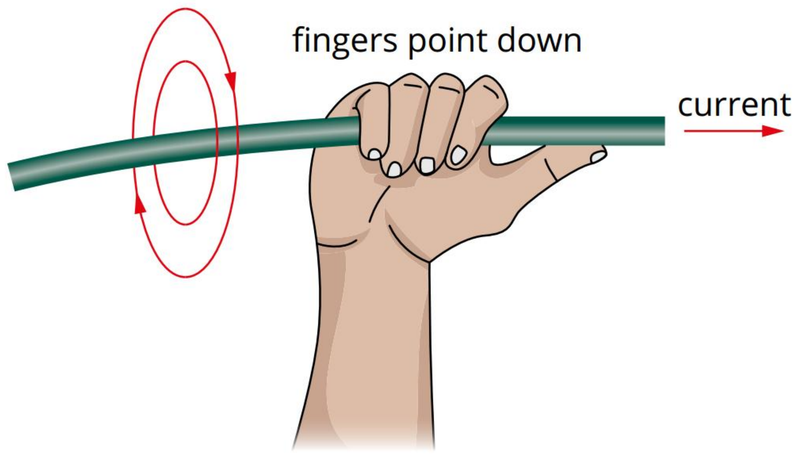


FIGURE 6.3.2 The right-hand grip rule can be used to find the direction of the magnetic field around a current-carrying wire, when the direction of the conventional current, I, is known.

Worked example 6.3.1

DIRECTION OF THE MAGNETIC FIELD

A current-carrying wire runs horizontally across a table. The conventional current direction, *I*, is running from left to right. Determine the direction of the magnetic field created by the current.	
Thinking	**Working**
Recall that the right-hand grip rule indicates the direction of the magnetic field.	Hold your hand as if your fingers were gripping the wire. Point your thumb to the right in the direction of the current flow. 
Describe the direction of the field in relation to the wire in simple terms, so that the description can be readily understood.	The magnetic field direction is perpendicular to the wire and follows the direction in which your fingers are pointing.

➤ Try yourself 6.3.1

DIRECTION OF THE MAGNETIC FIELD

A current-carrying wire runs along the length of a table. The conventional current direction, *I*, is running towards an observer standing at the near end. Determine the direction of the magnetic field created by the current as seen by the observer.

Strength of a magnetic field from a current-carrying wire

Straight, single-loop wires of a constant current have a field strength denoted by B (T). As you might expect, the magnetic field that comes from these wires is larger for greater currents, as there is more charge moving through the wire. For this reason, you would further expect that the magnetic field strength, B, is dependent on current, I.

The strength of the magnetic field generated by a single wire with current I at a distance r from the nearest point on the wire is given by:

$$B = \frac{\mu_0 I}{2\pi r}$$

where

B is the strength of the magnetic field (T)

μ_0 is the magnetic constant, also referred to as the **permeability of a vacuum**, $\mu_0 = 4\pi \times 10^{-7}\,\mathrm{T\,m\,A^{-1}}$

I is the current in the wire (A)

r is the distance from the wire (m).

Recall from Module 6.2 that the further away you are from a magnet, the further apart are its field lines and thus the weaker its magnetic field. Typically, this distance relation from a magnet is not easily defined; however, the magnetic field from a current-carrying wire presents a simpler system: the magnetic field decays radially in an outward direction from the wire, by the ratio $\frac{1}{r}$.

Worked example 6.3.2

STRENGTH OF THE MAGNETIC FIELD

A current-carrying wire is suspended in mid-air. A current of 2.0 mA is passed through it. Calculate the magnitude of the magnetic field at a distance of 150 cm from the wire. Ignore any effects from Earth's magnetic field.

Thinking	Working
Recall the formula giving the strength of a magnetic field from a current-carrying wire. Identify each variable with the quantities given.	$B = \frac{\mu_0 I}{2\pi r}$ $I = 2.0\,\text{mA}$ $r = 150\,\text{cm}$
Ensure that all units are in the appropriate form. The SI unit for current is amps and for distance is metres.	$2.0\,\text{mA} = 0.0020\,\text{A} = 2.0 \times 10^{-3}\,\text{A}$ $150\,\text{cm} = 1.50\,\text{m}$
Use the relevant quantities with their appropriate units to calculate the magnetic field. Give the final result in units of tesla.	$B = \frac{\mu_0 I}{2\pi r} = \frac{4\pi \times 10^{-7} \times (2.0 \times 10^{-3})}{2\pi \times 1.50}$ $= 2.7 \times 10^{-10}\,T$

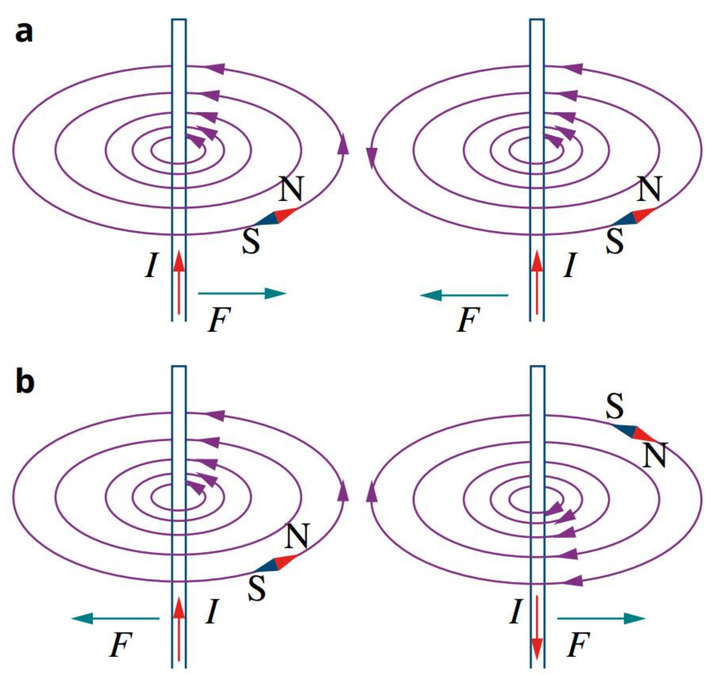


FIGURE 6.3.3 (a) Two current-carrying wires attract when current runs through them in the same direction. This is because the magnetic fields between the wires are in opposite directions, as you can see where the field lines are closest. (b) Two current-carrying wires repel when the current runs through them in opposite directions. This is because the magnetic fields are in the same direction.

➤ Try yourself 6.3.2

STRENGTH OF THE MAGNETIC FIELD

A current-carrying wire is suspended in mid-air. A current of 4.0 mA is passed through it. Calculate the magnitude of the magnetic field at a distance of 43 mm from the wire. Ignore any effects from Earth's magnetic field.

Magnetic fields between parallel wires

Two current-carrying wires arranged parallel to each other will each have their own magnetic field. The direction of the magnetic field around each wire is given by the right-hand grip rule. If the two wires are brought close together, their associated magnetic fields will interact, just as any two regular magnets would interact. The interaction could result in either an attraction or repulsion of the wires, depending on the direction of the magnetic fields between them (Figure 6.3.3). When the magnetic fields are in the opposite directions, this represents unlike poles, and so the wires attract. When the magnetic fields are in the same direction, the wires repel.

THREE-DIMENSIONAL FIELDS

Field lines can also be drawn for more-complex, three-dimensional fields such as that around the Earth or those around current-carrying loops and coils. Even for these more-complex fields, the right-hand grip rule can be used (Figures 6.3.4 and 6.3.5).

The direction of a magnetic field can be shown with a simple arrow on a field line when the field is travelling within the plane of a page (Figure 6.3.4), or a simple three-dimensional depiction (Figure 6.3.5).

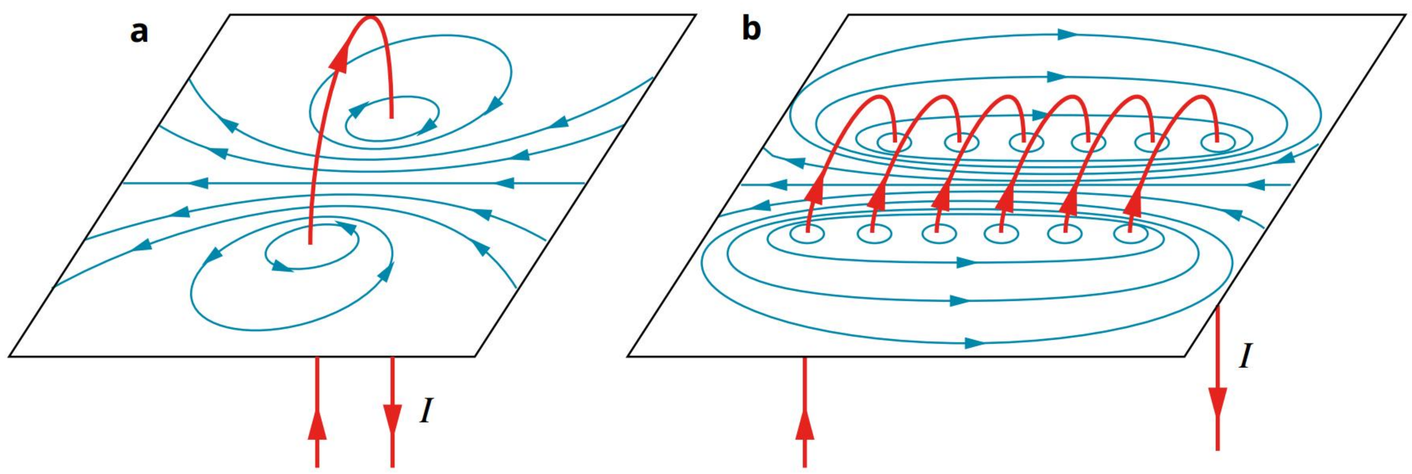


FIGURE 6.3.4 The formation of magnetic field lines around (a) a single current loop and (b) a series of loops illustrates the pattern of the magnetic field. The blue arrows indicate the direction of the magnetic field. The more concentrated the lines are inside the loops, the stronger the magnetic field is in this region.

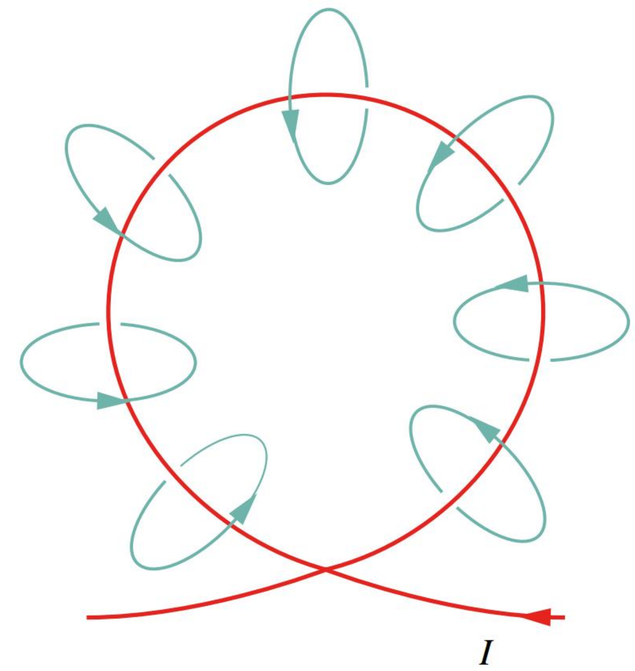


FIGURE 6.3.5 The blue arrows show the direction of the magnetic field in this three-dimensional representation of the magnetic field around a loop of wire in the plane of the page. Notice that the magnetic field is a circular shape, with no field lines crossing.

Figure 6.3.5 shows a three-dimensional representation of the magnetic field around a loop of wire. This same loop can also be represented in two dimensions using the following convention: when a field is running directly into or out of the plane of a page, dots are used to show a field coming out of the page and crosses are used to depict a field running directly into the page. This convention was adopted from the idea of viewing an arrow. The dot is the point of the arrow coming towards you, and the cross represents the tail feathers as the arrow travels away.

Figure 6.3.6 is a two-dimensional representation of the same magnetic field shown in Figure 6.3.5.

The strength of a field is depicted by varying the density of the dots and crosses. An increasing density indicates a strengthening of a field; decreasing density indicates a weakening of the field. More densely placed dots or crosses can also show a stronger area of the field. This is referred to as a non-uniform magnetic field.

As the magnetic field associated with a current-carrying coil is dependent upon the size of the current, the associated field may also be changing over time, either in magnitude, or, if the current is reversed, in direction.

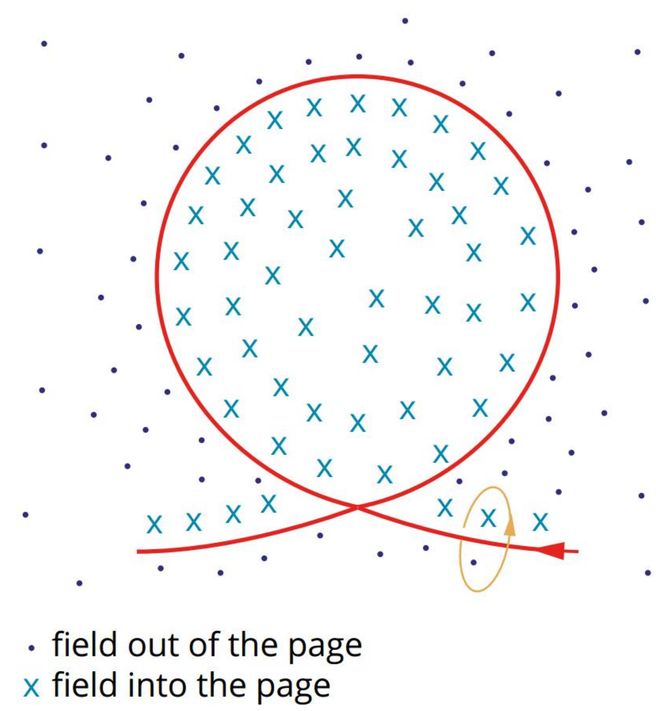


FIGURE 6.3.6 A two-dimensional representation of the same current-carrying loop depicted in Figure 6.3.5. Areas where the magnetic field is stronger are shown with a greater density of dots and crosses.

CREATING AN ELECTROMAGNET

The earliest magnets were all naturally occurring. If you wanted a magnet, you needed to find one. They were regarded largely as curiosities. Hans Christian Oersted's discoveries made it possible to manufacture magnets, making the widescale use of magnets possible.

An electromagnet, as the name implies, runs on electricity. It works because an electric current produces a magnetic field around a current-carrying wire. If the conductor is looped into a series of coils, then the magnetic field can be concentrated within the coils. The more coils, the stronger the magnetic field and, therefore, the stronger the electromagnet.

The magnetic field can be strengthened further by wrapping the coils around a core. Normally, the atoms in materials like iron point in random directions and the individual magnetic fields tend to cancel each other out. However, the magnetic field produced by coils wrapped around an iron core can force the atoms within the core to point in one direction. Their individual magnetic fields add together, creating a stronger magnetic field.

The strength of an electromagnet can also be changed by varying the amount of electric current that flows through it.

The direction of the current creates poles in the electromagnet. The poles of an electromagnet can be reversed by reversing the direction of the electric current.

Today, electromagnets are used directly to lift heavy objects (Figure 6.3.7), as switches and relays, and as a way of creating new permanent magnets by aligning the atoms within magnetic materials.

FIGURE 6.3.7 A large electromagnet is used to lift waste iron and steel at a scrapyard. Valuable metals such as these are separated and then recycled.

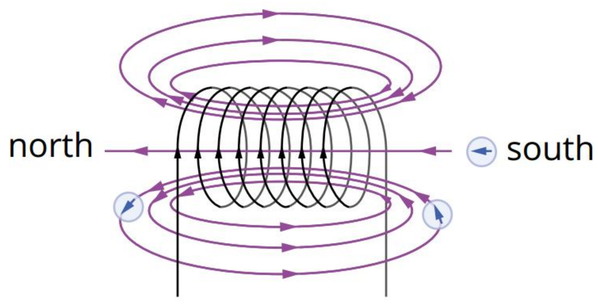


FIGURE 6.3.8 This solenoid has current running upwards at the front of the coil and downwards at the back. This arrangement creates an an effective 'north' end at the left and a 'south' end at the right. The compass, represented by arrows in circles, points in the direction of the field lines.

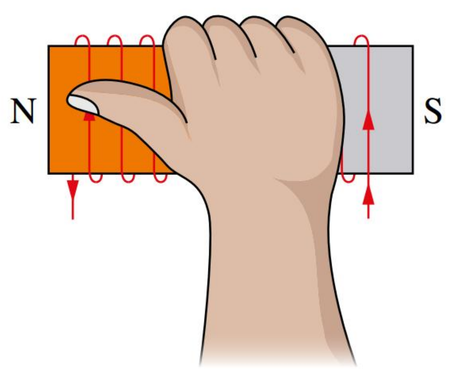


FIGURE 6.3.9 The right-hand grip rule for a solenoid

THE MAGNETIC FIELD AROUND A SOLENOID

If many loops are placed side by side, their fields all add together and there is a much stronger effect. This can easily be achieved by winding many turns of wire into a coil termed a **solenoid**. The field around the solenoid is like the field around a normal bar magnet. The direction of the overall magnetic field can be determined by considering the field around each current-carrying wire making up the loop, and adding these together. The direction of the field of the solenoid depends on the direction of the current in the wire making up the solenoid (Figure 6.3.8).

A simple way to determine which end of a solenoid is which pole is to use a version of the right-hand grip rule. Curl your right hand in the direction of the current coils (Figure 6.3.9); then the direction in which your thumb points is the direction of the magnetic field emerging from the middle of the solenoid. This end is the north pole (N), while the other end is the south pole (S). Note the difference between this and the right-hand grip rule used previously. For a coiled wire, you can use your fingers to represent the current and thumb to represent the magnetic field. For a straight wire, your fingers represent the field and your thumb represents the direction of the current in the wire.

The strength of a magnetic field inside a solenoid

Looking at the magnetic field in Figure 6.3.8, you will notice that the field lines flatten out somewhat inside the solenoid. If the solenoid were to become longer, the field lines would flatten out more and more until an essentially uniform, constant field formed inside the solenoid. With this approximation, you can discuss the strength of a magnetic field inside a solenoid.

In Module 6.2 you learnt that the magnetic field at a point in space is the vector addition of all contributions to the magnetic field at this point. For this reason, it is not surprising that when two loops with current in the same direction are placed next to each other they will produce a magnetic field that is stronger than that produced by either loop alone. From this you can determine that the magnetic field inside a solenoid will depend on the number of loops. However, given that the magnetic field also decays with distance, the strength of the field in a solenoid also depends on the distance between the loops. The number of loops divided by the total length of the solenoid will give the number of loops per unit length of solenoid. It is this quantity that is used in our expression for the magnetic field inside a solenoid.

The magnetic field of a solenoid is given by $B = \mu_0 n I$

where

B is the strength of the magnetic field (T)

μ_0 is the magnetic constant, $\mu_0 = 4\pi \times 10^{-7}\,\mathrm{T\,m\,A^{-1}}$

n is the number of loops per metre $= \dfrac{N}{L}$ for N loops in a solenoid of length L (m)

I is the current in the conductor (A).

This can also be expressed as $B = \dfrac{\mu_0 N I}{L}$.

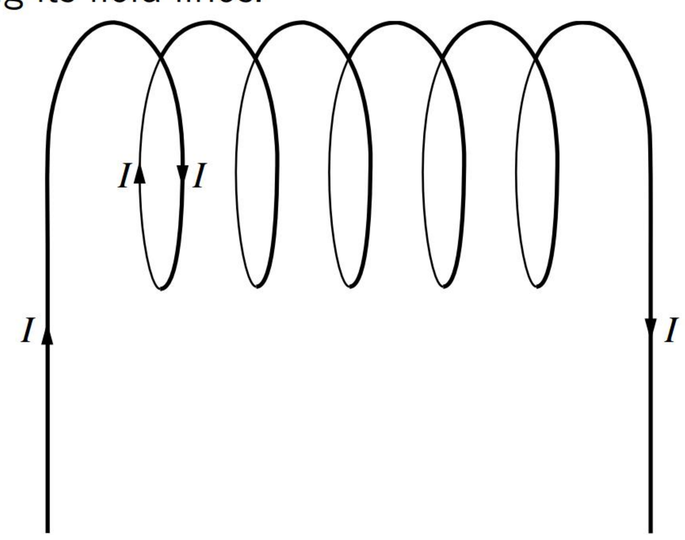
Worked example 6.3.3

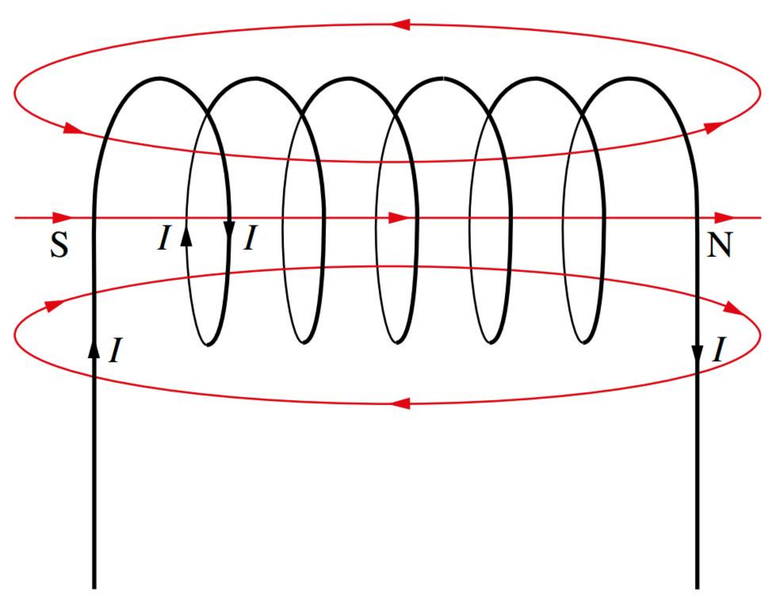
CALCULATING THE STRENGTH OF A MAGNETIC FIELD INSIDE A SOLENOID

a Calculate the strength of the magnetic field inside a 60.0 cm long solenoid that has 80 loops and a current of 3.5 A flowing through it.

Thinking	Working
Ensure that the variables are in their standard units.	$L = 60\,\text{cm} = 0.60\,\text{m}$ $N = 80$ $I = 3.5\,\text{A}$
Apply the equation for magnetic field strength.	$B = \mu_0 nI = B = \dfrac{\mu_0 NI}{L}$
Substitute in the correct values to ascertain the strength of the magnetic field.	$B = \dfrac{4\pi \times 10^{-7} \times 80 \times 3.5}{0.60}$ $= 5.9 \times 10^{-4}\,\text{T}$

b Determine the direction of the magnetic field produced in the solenoid shown below, by sketching its field lines.



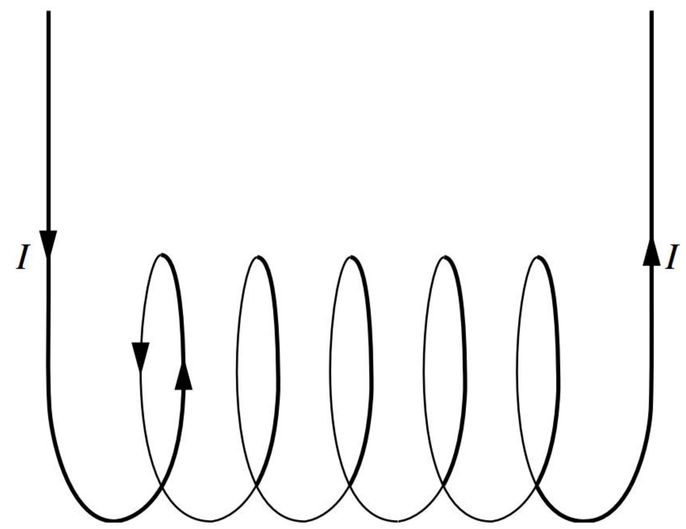
Thinking	Working
Align the fingers of your right hand in the same direction as the current running through the solenoid and stick your thumb out. Your thumb will be in the direction of the magnetic field from the solenoid.	

➤ Try yourself 6.3.3

CALCULATING THE STRENGTH OF A MAGNETIC FIELD INSIDE A SOLENOID

a Calculate the strength of the magnetic field inside a 20.0 mm long solenoid that has 120 loops and a current of 1.2 mA flowing through it.

b Determine the direction of the magnetic field produced in the solenoid shown below, by sketching its field lines.



6.3 Review

SUMMARY

- A moving charge results in a magnetic field.
- An electrical current produces a magnetic field that is circular around a current-carrying conductor. The direction of the field is given by using the right-hand grip rule, when considering the direction of the conventional current.
- The magnetic field strength at a distance r from a current-carrying wire is given by $B = \frac{\mu_0 I}{2\pi r}$.
- A three-dimensional depiction of a magnetic field can be made by drawing dots to represent field lines coming out of the page, and crosses to represent field lines going into the page.
- The direction of a magnetic field through a solenoid can be determined by applying the right-hand grip rule to the current-carrying loops.
- The magnetic field inside a solenoid is uniform, with magnitude given by $B = \mu_0 nI$.
- By expressing the number of loops per metre as $n = \frac{N}{L}$, this can be re-written as $B = \frac{\mu_0 NI}{L}$.

KEY QUESTIONS

Describe

1 Identify the direction of a magnetic field represented by crosses, and one represented by dots.

2 Describe a solenoid.

3 List three ways in which you could increase the strength of an electromagnet.

4 State the relationship between the number of coils in a solenoid and its magnetic field.

5 Identify the relationship between the distance from a current-carrying wire and the strength of the magnetic field.

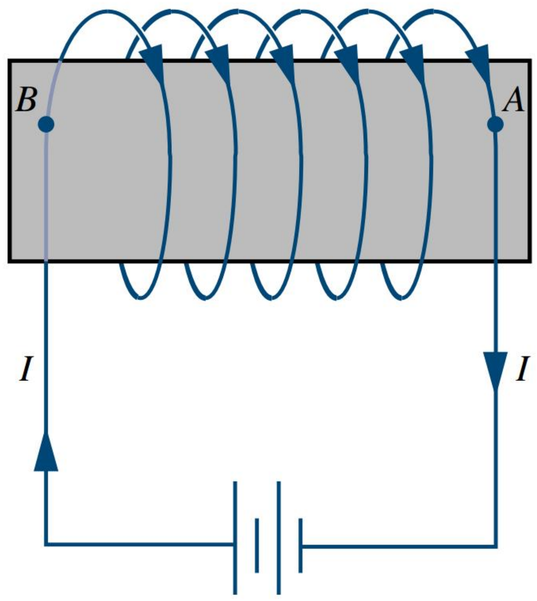
Apply

6 Calculate the strength of the magnetic field inside a solenoid that has 110 loops per metre and a current of 2.3 mA flowing through it.

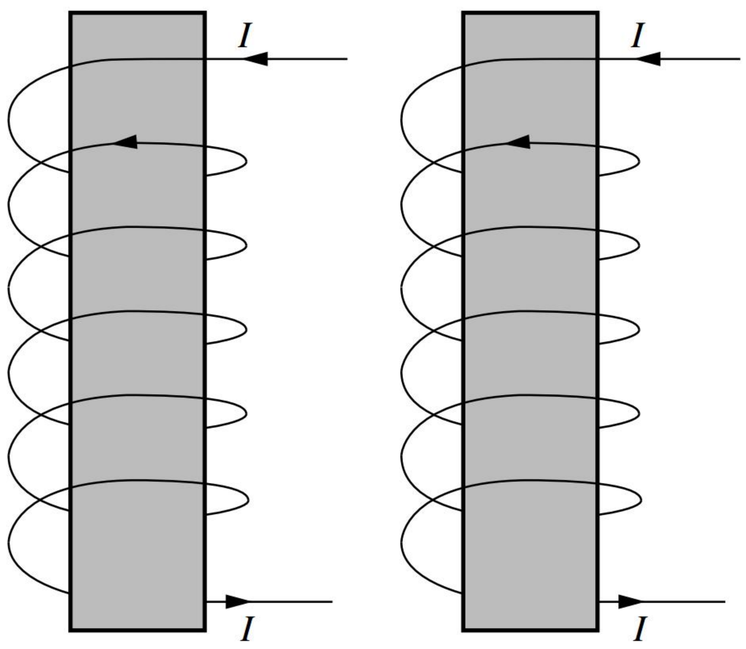
7 Describe how a magnetic field is induced by a charged particle; compare its electric and magnetic fields.

8 Sketch the direction of a magnetic field induced by a wire carrying current vertically upwards.

9 Identify which end, A or B, represents the north pole of the current-carrying solenoid shown below.



10 Describe what will happen to two solenoids that are arranged next to each other as shown. The solenoids are the same length, and have the same number of turns and current flowing through them. Carefully explain your reasoning.



Analyse

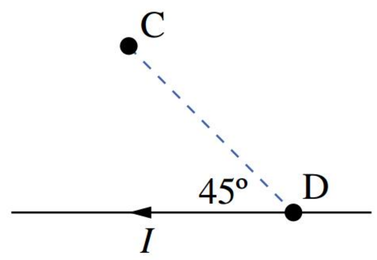
11 Christos measures the magnetic field strength, *B*, at a distance *r* away from the wire with a current *I*.

a Determine the field strength at a distance of 2*r* away from the wire.

The current in the wire is now changed to 3*I*.

b Determine the field strength at the same distance from the wire.

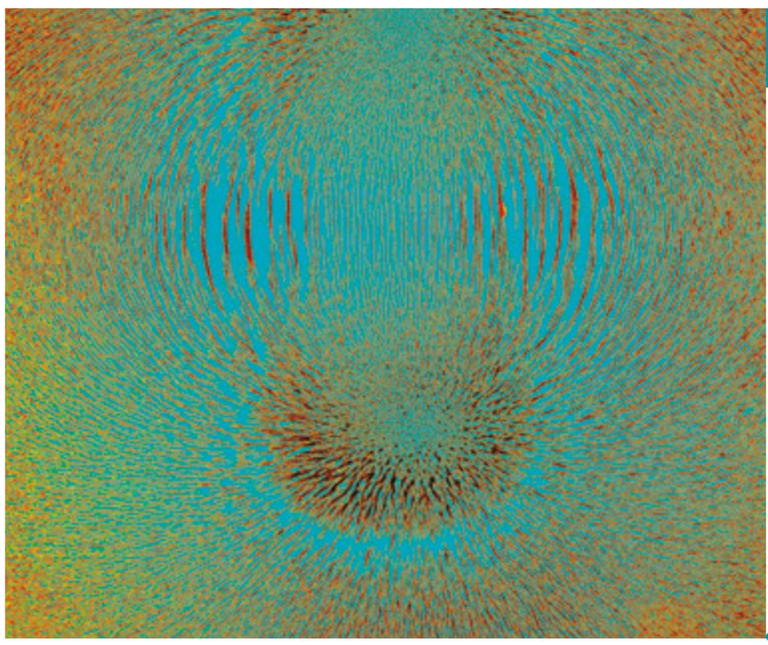
12 Calculate the magnitude of the magnetic field strength at point C in the diagram below, given that C and D are 3.0 cm apart and make a 45° angle with the wire. The wire shown is carrying a current of 2.0 A.



13 Jane wishes to determine the current running through a wire, but does not have an ammeter present. She arranges the wire into a 5.0 m coil with exactly 10 loops and measures the magnetic field within the solenoid to be 0.37 μT. Calculate the strength of the current running through the wire.

14 Calculate the number of turns a solenoid should have to produce a magnetic field of 1.0053 T inside it if it carries a current of 4.0 A and is 10.0 cm long.

6.4 Magnetic force on a current-carrying wire



BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- describe the force experienced by current-carrying wires in a magnetic field
- solve problems involving the magnetic force on a current-carrying wire
- determine the magnitude and direction of the magnetic force on a current-carrying wire
- calculate how the magnetic force on a current-carrying wire changes at different angles to the field
- interpret data relating to the force acting on a conductor in a magnetic field
- predict the behaviour of coils made to rotate in a magnetic field.

A current-carrying wire induces a magnetic field that can interact with other magnetic fields. You have learnt from your theory of magnetic and electric fields that interaction with these fields constitutes a force acting on an object. Hence it would be expected that current-carrying wires would experience a force in the presence of a magnetic field. This is the theory behind the operation of electric motors.

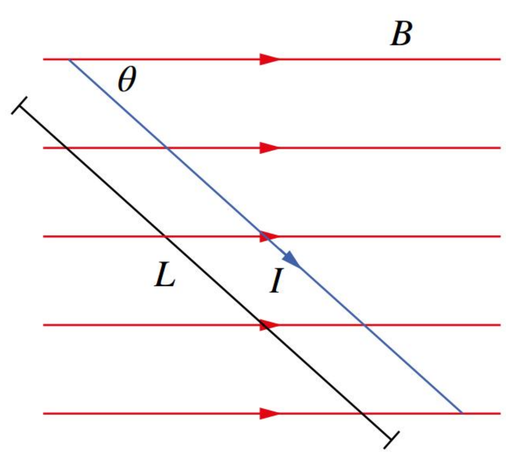


FIGURE 6.4.1 A current-carrying wire of length L is at an angle to a magnetic field.

THE FORCE ON A CURRENT-CARRYING WIRE

The force (F) acting on a wire in a magnetic field (B) is related to the total amount of charge moving through the wire, which depends on its current (I), and the total length of the wire (L) and angle between the wire and the magnetic field (θ) (Figure 6.4.1). This relationship is expressed in the following formula:

$F = BIL\sin\theta$

where

F is the force on the wire perpendicular to the magnetic field (N)

B is the strength of the magnetic field (T)

I is the current in the wire (A)

L is the length of the wire (m)

θ is the angle between the wire and the magnetic field (°).

The force experienced by a current-carrying conductor is a vector quantity. When the component of the conductor is perpendicular to the magnetic field, the conductor experiences its maximum force. The conductor experiences zero magnetic force when it is parallel to the magnetic field.

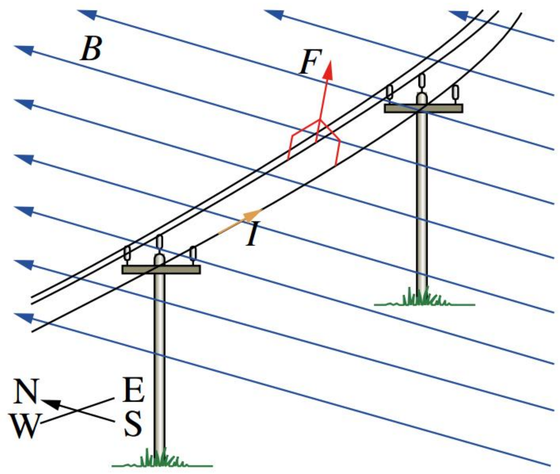
Furthermore, since (in general) the net force at a point is the sum of all the contributing forces, you can add up all the contributions from different wires. If you happen to have a coil and there is more than one loop in the coil, then the total force is the number of loops multiplied by the magnetic force from each loop. That is, $F = nBIL$, where n is the number of turns of wire.

Note that this is a calculation for the magnitude of the force. The direction stays the same as if the conductor were perpendicular to the field.

Worked example 6.4.1

MAGNITUDE OF THE FORCE ON A CURRENT-CARRYING WIRE

Determine the magnitude of the force due to Earth's magnetic field that acts on 1.0 m of a suspended power line running east-west near the equator at the moment it carries a current of 100.0 A from west to east. Assume that the strength of Earth's magnetic field at this point is 5.0×10^{-5} T.

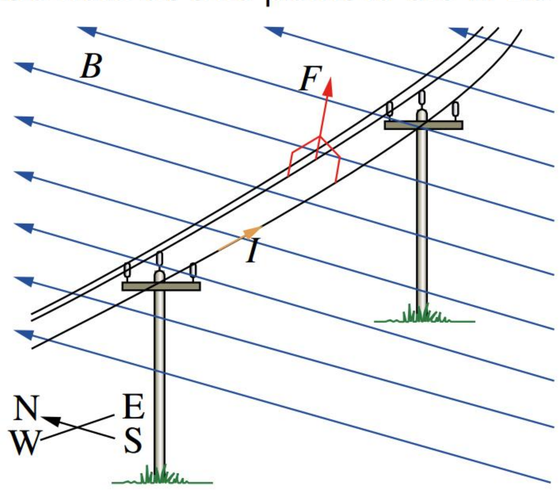


Thinking	Working
Check the direction of the power line and determine whether a force will apply. Forces only apply to the component of the line perpendicular to the magnetic field.	As the current is running west-east and the Earth's magnetic field runs south-north, the current and the field are at right angles, and a force will exist.
Establish which quantities are known and which are required.	$F = ?$ $B = 5.0 \times 10^{-5}$ T $I = 100$ A $L = 1.0$ m $\theta = 90°$
Substitute values into the force equation and simplify.	$F = BIL\sin\theta$ $= 5.0 \times 10^{-5} \times 100 \times 1.0 \times \sin 90°$ $= 5.0 \times 10^{-3}$
Express the final answer in an appropriate form with a suitable number of significant figures. Note that only magnitude has been requested, so do not include direction.	$F = 5.0 \times 10^{-3}$ N

➤ Try yourself 6.4.1

MAGNITUDE OF THE FORCE ON A CURRENT-CARRYING WIRE

Determine the magnitude of the force due to Earth's magnetic field that acts on 1.0 m of a suspended power line running east-west near the equator at the moment it carries a current of 50.0 A from west to east. Assume that the strength of Earth's magnetic field at this point is 5.0×10^{-5} T.



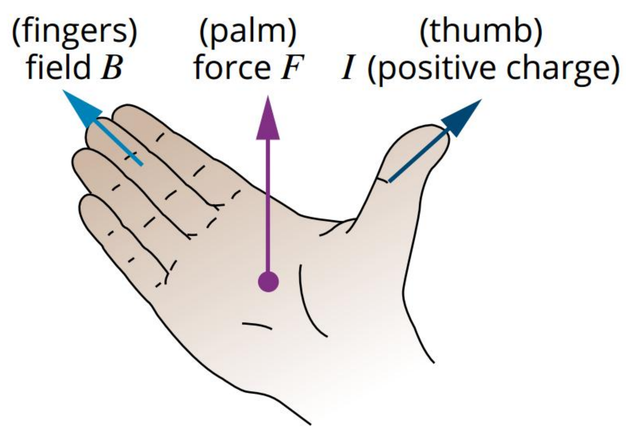


FIGURE 6.4.2 The right-hand slap rule: Point the thumb of your right hand in the direction of the conventional current and the fingers in the direction of the magnetic field. The force on the charge will be in the direction to which your palm points.

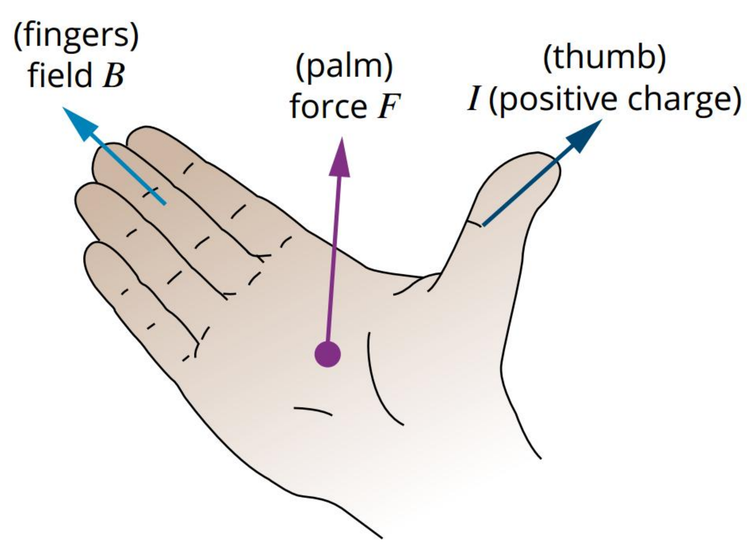
Determining the direction of the force

The direction of the force acting on the wire when the wire is at right angles to the magnetic field can be determined by a simple mnemonic called the **right-hand slap rule**. Open your palm out flat with your thumb perpendicular to your fingers (Figure 6.4.2). Point your thumb in the direction of the conventional current, and your outstretched fingers in the direction of the magnetic field. The direction of the resulting force on the current is the direction in which your palm is pointing.

Worked example 6.4.2

DIRECTION OF THE FORCE ON A CURRENT-CARRYING WIRE

A current balance is used to measure the force from a magnetic field on a wire of length 5.0 cm running perpendicular to the magnetic field. The conventional current direction in the wire is from left to right. The magnetic field can be considered to be running into the page. Determine the direction of the force on the wire.

Thinking	Working
The right-hand slap rule is used to determine the direction of the force. 	Align your hand so that your fingers are pointing in the direction of the magnetic field, i.e. into the page. Align your thumb so it is pointing right, in the direction of the current. Your palm should be facing upwards. That is the direction of the force applied by the magnetic field on the wire.
State the direction in terms of the other directions included in the question. Make the answer as clear as possible to avoid any misunderstanding.	The force on the wire is acting vertically upwards.

➤ Try yourself 6.4.2

DIRECTION OF THE FORCE ON A CURRENT-CARRYING WIRE

A current balance is used to measure the force from a magnetic field on a wire of length 5.0 cm running perpendicular to the magnetic field. The conventional current direction in the wire is from left to right. The magnetic field can be considered to be running out of the page. Determine the direction of the force on the wire.

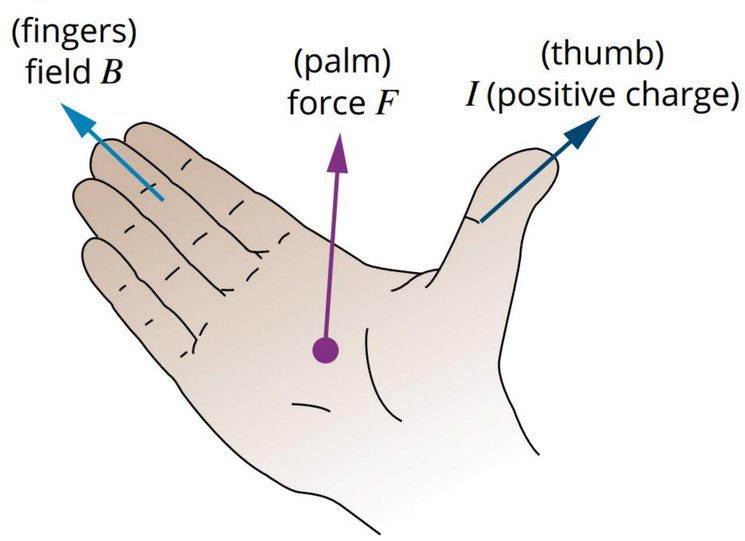
Worked example 6.4.3

FORCE ON A CURRENT-CARRYING WIRE AND DIRECTION

The Amundsen–Scott South Pole Station sits at a point that can be considered to be at Earth's South Magnetic Pole (which behaves like the north pole of a magnet).

Assume the strength of Earth's magnetic field at this point is 5.0×10^{-5} T.

a Determine the magnitude and direction of the magnetic force on a 2.0 m length of wire carrying a conventional current of 10.0 A vertically up the exterior wall of one of the buildings.	
Thinking	**Working**
Forces only apply to the components of the wire running perpendicular to the magnetic field. The direction of the magnetic field at the southern magnetic pole will be almost vertically upwards.	The section of the wire running up the wall of the building will be parallel to the magnetic field, *B*. Hence, no force will apply.
State your answer. A numeric value is required. Since there is no force, it is not necessary to state a direction.	$F = 0\,\text{N}$

b Determine the magnitude and direction of the magnetic force on a 2.0 m length of wire carrying a conventional current of 10.0 A running horizontally right to left across the exterior of one of the buildings.	
Thinking	**Working**
Forces only apply to the components of the wire running perpendicular to the magnetic field. The direction of the magnetic field at the southern magnetic pole will be almost vertically upwards (that is, out of the ground).	The section of the wire running horizontally across the building will be perpendicular to the magnetic field, *B*. A force, *F*, with a strength equivalent to *BIL* will apply.
Identify the known quantities.	$F = ?$ $B = 5.0 \times 10^{-5}\,\text{T}$ $I = 10.0\,\text{A}$ $L = 2.0\,\text{m}$ $\theta = 90°$
Substitute into the appropriate equation and simplify.	$F = BIL\sin\theta$ $= 5.0 \times 10^{-5} \times 10.0 \times 2.0 \times \sin 90°$ $= 1.0 \times 10^{-3}\,\text{N}$
 The direction of the magnetic force is also required to fully specify the vector quantity. Determine the direction of the magnetic force using the right-hand slap rule.	Align your hand so that your fingers are pointing in the direction of the magnetic field, i.e. vertically up. Align your thumb so it is pointing left, in the direction of the current. Your palm should be facing outwards (towards the building). That is the direction of the force applied by the magnetic field on the wire.
State the magnetic force in an appropriate form with a suitable number of significant figures. Include the direction to fully specify the vector quantity.	$F = 1.0 \times 10^{-3}\,\text{N}$ outwards

➤ Try yourself 6.4.3

FORCE ON A CURRENT-CARRYING WIRE AND DIRECTION

Santa's house sits at a point that can be considered the Earth's Magnetic North Pole (which behaves like the south pole of a magnet).

Assume the strength of Earth's magnetic field at this point is 5.0×10^{-5} T.

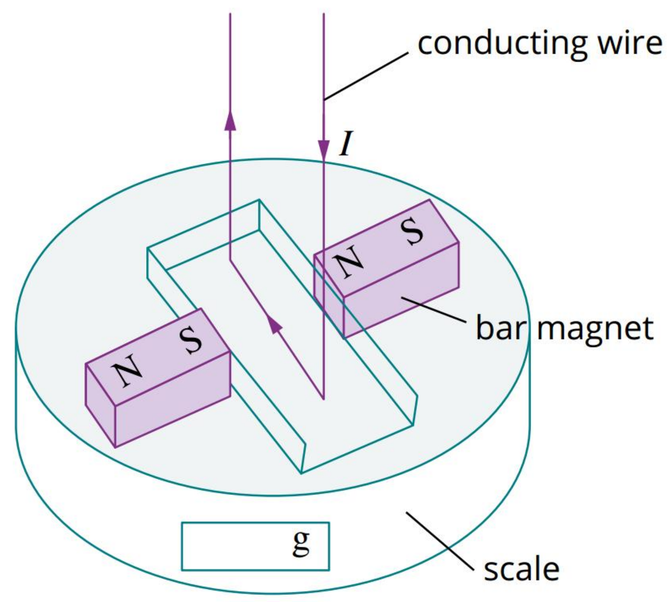
a Calculate the magnetic force and its direction on a 2.0 m length of wire carrying a conventional current of 10.0 A vertically up the outside wall of Santa's house.

b Calculate the magnetic force and its direction on a 2.0 m length of wire carrying a conventional current of 10.0 A running horizontally right to left across the outside of Santa's house.

Worked example 6.4.4

EXPERIMENTAL DATA OF THE FORCE ACTING ON A CONDUCTOR

A student sets up the following experiment to test the magnetic force on a current-carrying wire for various currents. The conducting wire is connected to a variable power source.

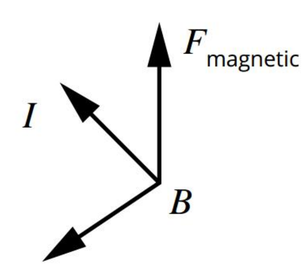


By measuring the weight force for each current and using the third law of motion, they are able to calculate the magnetic force acting on the wire.

They collect the following data:

Current (A)	Mass (g)	Magnetic force (N)
1.0	0.03	0.0003
1.5	0.05	0.0005
2.0	0.06	0.0006
2.5	0.08	0.0008
3.0	0.09	0.0009
3.5	0.11	

Complete the table by calculating the missing magnetic force.

Thinking	Working
Using the third law of motion and the right-hand slap rule, draw a diagram to show how the weight force can be used to calculate the magnetic force.	The right-hand slap rule shows how the force on the wire will be pointed upwards. 

	According to the third law of motion, there will be an equal and opposite force downwards which will be detected by the scale and appear as a weight force.
Calculate the magnetic force for the missing value. Remember the equation for the weight force (the force due to gravity) is $F_g = mg$. Remember that the acceleration due to gravity, g, is equal to 9.8 m s^{-2} near the surface of the Earth. Note that the mass is given in grams and so will need to be converted into SI units.	$F = mg = (0.11 \div 1000) \times 9.8$ $= 0.0011$ N

Current (A)	Mass (g)	Magnetic force (N)
1.0	0.03	0.0003
1.5	0.05	0.0005
2.0	0.06	0.0006
2.5	0.08	0.0008
3.0	0.09	0.0009
3.5	0.11	0.0011

➤ Try yourself 6.4.4

EXPERIMENTAL DATA OF THE STRENGTH OF A MAGNETIC FIELD

A similar experiment is setup to test the magnetic force on a current-carrying wire for various currents but using a different-sized magnet.

By measuring the weight force for each current and using the third law of motion, they are able to calculate the magnetic force acting on the wire for each value of the current.

They collect the following data.

Current (A)	Mass (g)	Magnetic force (N)
1.0	0.024	0.00024
1.5	0.036	0.00035
2.0	0.048	0.00047
2.5	0.060	0.00059
3.0	0.071	0.00070
3.5	0.084	

Complete the table by calculating the missing magnetic force.

Worked example 6.4.5

FORCE ON A CURRENT-CARRYING WIRE AT AN ANGLE TO THE FIELD

Clint is investigating the force on a current-carrying wire in a magnetic field. He has a 3.0 m section of wire with current 0.200 A that is at an angle of 30.0° to a magnetic field of strength 1.3×10^{-3} T. Calculate the force he would expect to detect on the wire.

Thinking	Working
Identify the correct formula to use.	$F = BIL\sin\theta$.
Identify the known values.	$F = ?$ $B = 1.3 \times 10^{-3}$ T $I = 0.200$ A $L = 3.0$ m $\theta = 30°$
Use the above formula with the known values to calculate the force.	$F = BIL\sin\theta$ $= 1.3 \times 10^{-3} \times 0.200 \times 3.0 \sin 30°$ $= 3.9 \times 10^{-4}$ N

➤ Try yourself 6.4.5

FORCE ON A CURRENT-CARRYING WIRE AT AN ANGLE TO THE FIELD

Susie is investigating the force on a current-carrying wire in a magnetic field. She has a 0.15 m section of wire with current 0.0500 A at an angle of 45° to a magnetic field of strength 2.5×10^{-3} T. Calculate the force she would expect to detect on the wire.

MOTORS

Physicists have always been interested in the relationship between electricity and magnetism because they wanted to understand the basic workings of the universe. For the world at large, however, this understanding provided a more practical form of excitement. It enabled the generation and use of electricity on a large scale. One of the most obvious applications of the understanding of electromagnetism gained in the 19th century is the electric motor.

Consider a single square coil of wire, with vertices ABCD, carrying a current, I, in a magnetic field, B (Figure 6.4.3).

Initially the wire coil is aligned horizontally with the magnetic field, B (Figure 6.4.3a). Sides AD and BC are parallel to the magnetic field, so no magnetic force will act on them. Sides AB and CD are perpendicular to the field, so both of these sides will experience a magnetic force. Using the right-hand slap rule, there is a downwards force on AB and an upwards force on CD. These two forces will act together on the coil and cause it to rotate anticlockwise. If the coil is free to turn it will move towards the position shown in Figure 6.4.3b.

In Figure 6.4.3b, there will be a magnetic force acting on every side of the coil. However, the forces acting on sides AD and BC will be equal and opposite in direction. They will tend to stretch the coil outwards but won't affect its rotation. The forces on sides AB and CD will remain and the coil will continue to rotate anticlockwise.

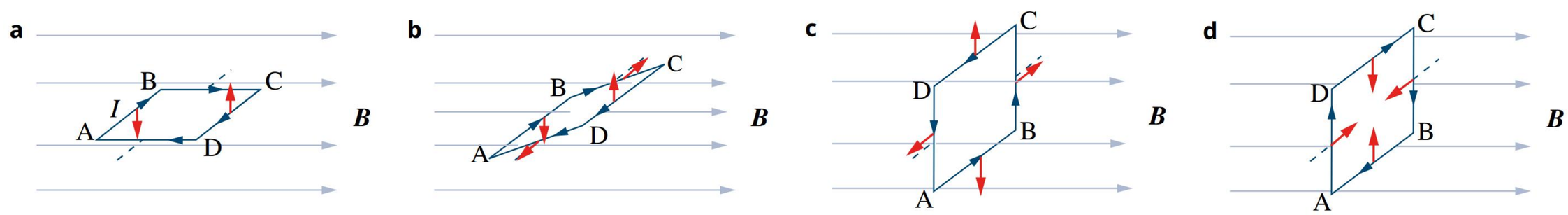


FIGURE 6.4.3 A magnetic force acts on each side of a current-carrying square wire coil in a magnetic field, *B*.

As the coil rotates to the position shown in Figure 6.4.3c, the forces acting on each side are such that they will tend to keep the coil in this position. The force on each side will act outwards from the coil. There are no turning forces at this point, but any further rotation will induce a force in the opposite direction causing the coil to rotate clockwise, back to this perpendicular position. For the coil to continue to rotate anticlockwise at this point, the current direction needs to be reversed. This is shown in Figure 6.4.3d. With the current reversed, all of the forces are reversed, and provided the coil has a little momentum to get it past the perpendicular position, it will continue to rotate anticlockwise. This ability to reverse the current direction at the point where the coil is perpendicular to the magnetic field is a key design feature in DC motors.

Practical motors will have many sets of coils of many turns each, spaced at an angle to each other. The coils are wound around a soft iron core to increase the magnetic field that passes through them. The whole arrangement of core and coils is called an armature.

Generally speaking, the larger the turning force in an electric motor the better. This is achieved by the use of a strong magnetic field, a large number of turns of wire in each coil, a high current and a large area of coil. All this adds to the cost, so when designing an electric motor, each aspect may be compromised to some extent in light of its potential use.

6.4 Review

SUMMARY

- A current-carrying wire will experience a force when placed in a magnetic field.
  - The force is at a maximum when the wire is at right angles to the magnetic field.
  - The force is zero when the wire is placed parallel to the magnetic field.
  - The magnetic force on a current-carrying wire within a magnetic field is $F = BIL \sin \theta$.
  - The direction of the force is given by the right-hand slap rule in which the force travels out of the palm of the hand when the thumb and fingers are orientated in the direction of the (conventional) current and magnetic field respectively.
- The electric motor is a direct application of the force produced by a magnetic field on a current-carrying wire.

KEY QUESTIONS

Describe

1 Identify the quantities used by the right-hand slap rule and how they describe the direction of the magnetic force.

2 A current-carrying wire is at an angle, θ, to a magnetic field. State the values of θ at which the magnitude of the magnetic force acting on the wire is at:

a a minimum

b a maximum.

6.4 Review *continued*

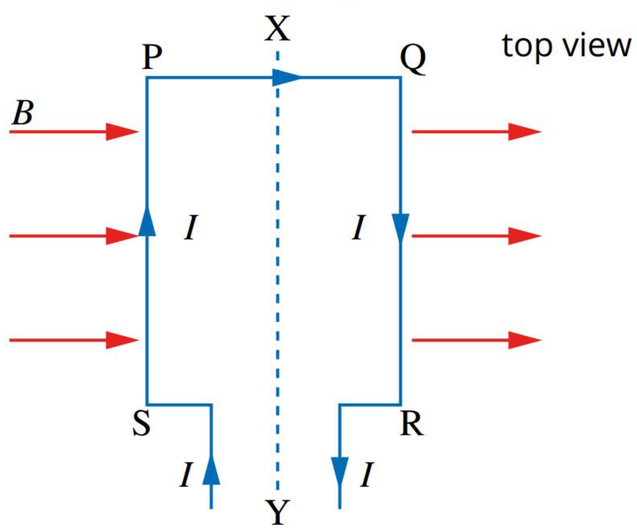
3 Select the correct options in bold to complete the following sentence.

The force on a current-carrying wire in a magnetic field is **perpendicular / parallel** to the field and **perpendicular / parallel** to the current.

Apply

4 Indicate the situation(s) where the magnitude of the turning force of a motor is at a maximum with respect to the axis of rotation.

5 Determine the direction of the force on the length of wire marked PQ in a rectangular loop of wire carrying a current, *I*, in a magnetic field, *B*, as shown below.



6 Imogen places a current-carrying wire perpendicular to a uniform magnetic field and measures the magnetic force acting on it.

a Describe how the direction of the force would change if the angle of the wire is changed to 45°.

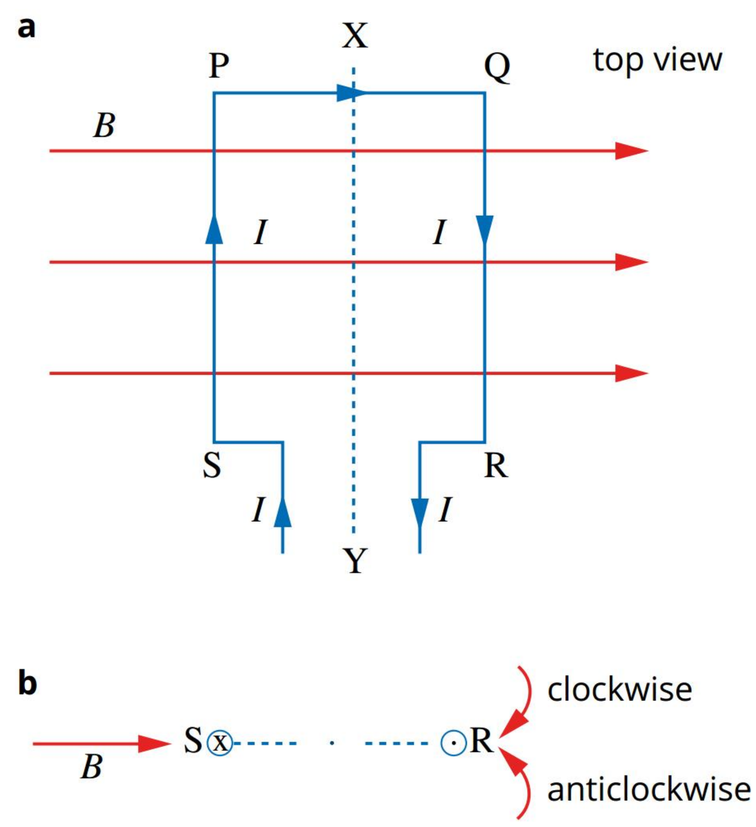
b Describe how the magnitude of the force would change if the current is doubled and the angle is reduced to 30°.

The information below applies to questions **7–10**.

Part (a) of the diagram below depicts a top view of a single current-carrying coil in an external magnetic field *B*.

Part (b) of the diagram is the corresponding cross-sectional view as seen from point Y. The following data apply:

$B = 0.10\,\text{T}$, PQ = 2.0 cm, PS = QR = 5.0 cm, $I = 2.0\,\text{A}$.



7 Calculate the magnitude and direction of the magnetic force acting on side PS.

8 Calculate the magnitude and direction of the magnetic force acting on side QR.

9 Determine the magnitude of the force on side PQ.

10 Determine the direction, as seen from Y, in which the coil rotates. The coil is free to rotate about an axis through XY.

Analyse

The information below applies to questions **11–14**.

A student sets up the following experiment to test the magnetic force on a current-carrying wire for various currents.

By measuring the weight force for each current and using the third law of motion, they are able to calculate the magnetic force acting on the wire for each value of the current.

They collect the following data.

Current (A)	Mass ($\times 10^{-5}$ kg)	Magnetic force ($\times 10^{-4}$ N)
1.0	2.54	2.49
1.5	3.81	3.74
2.0	5.08	4.98
2.5	6.35	6.23
3.0	7.62	7.47
3.5	8.89	

11 Complete the table by calculating the missing magnetic force.

12 Create a graph of the independent and dependent variables of the investigation.

13 Interpret the relationship between current and magnetic force.

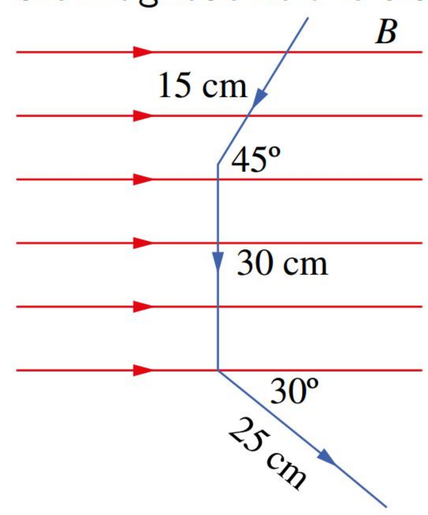
14 If the length of the conducting wire within the field is 3.0 cm, calculate the strength of the magnetic field between the two magnets.

15 An east–west power line of length 8.00 m is suspended between two towers. Assume that the strength of the magnetic field of the Earth in this region equals 4.5×10^{-5} T from south to north.

a Calculate the magnitude and direction of the magnetic force on this power line at the moment it carries a current of 50.0 A from east to west.

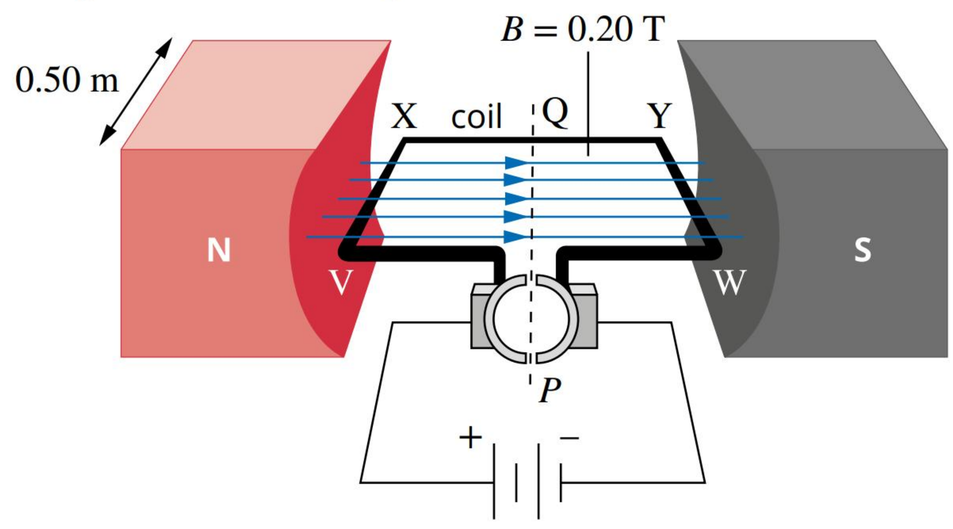
b Over time, the ground underneath the eastern tower subsides, so that the power line is lower at that tower. Assess whether the magnitude of the magnetic force on the power line is greater than before, less than before or the same as before. Assume all other factors are the same.

16 Consider the wire below, with the current running through the wire is 3.0 A. Calculate the total force acting on the wire and give the direction of this force if the magnetic field is 0.350 T.



The following information applies to questions 17–19.

The diagram shows a simplified version of a DC motor.

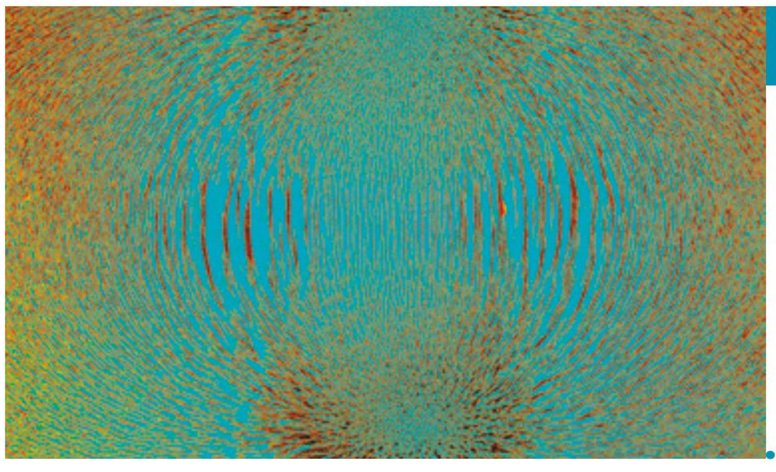


17 Calculate the magnitude of the force on segment WY when a current of 1.0 A flows through the coil.

18 Determine the direction in which the coil will begin to rotate. Explain your reasoning.

19 Determine whether each of the following actions would cause the coil to rotate faster: increasing the current, increasing the magnetic field strength, and increasing the length of the coil in the magnetic field.

6.5 Magnetic force on a single charge



BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- describe and predict the behaviour of a moving electric charge in a magnetic field
- calculate the magnitude and direction of the magnetic force acting on a moving charged particle
- understand how this physics can be put into action in building and using particle accelerators.

An electric current is a flow of electric charges. These may be electrons in a metal wire, electrons and mercury ions in a fluorescent tube or cations and anions in an electrolytic cell. The nature of the flowing charge that makes up the current does not matter. A magnetic field is produced around the flow of charge, and a force is experienced within this field (Figure 6.5.1). In each case, it is the total rate of flow of charge (the current) that determines the field produced and the magnitude of the force.

MAGNETIC FORCE ON CHARGED PARTICLES

In Module 6.4 you learnt that a current-carrying wire in a magnetic field will experience a magnetic force. If you examine what constitutes a current (a flow of charge) then you can predict the force that an individual moving charged particle in a magnetic field will experience.

The principle behind a cathode ray tube (CRT) is that a charged particle moving within a magnetic field will experience a force. In Figure 6.5.1, a beam of electrons in a CRT is experiencing a force due to a magnetic field. The force causes the beam of electrons to bend. The magnitude of the force is proportional to the strength of the magnetic field, B, the component of the velocity of the charge that is perpendicular to the magnetic field and the charge on the particle. In Module 6.4 you investigated the manner in which a magnetic force acts on a current-carrying wire.

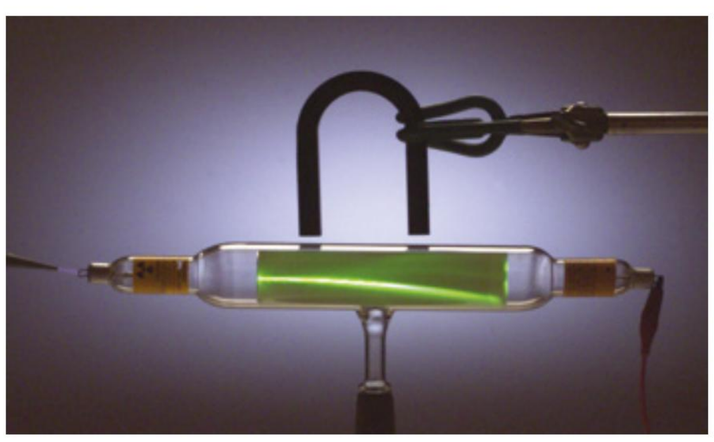


FIGURE 6.5.1 The electron beam of a cathode ray tube is deflected by a magnet.

The formula $F = BIL\sin\theta$ is used to determine the force acting on the overall wire. The current in a given wire, however, is nothing more than the flow of charged particles. You can work backwards from the force on a charged current to investigate how this magnetic force behaves with free particles:

$$F = BIL\sin\theta$$

Current, I, is defined as the rate of flow of charge: $I = \frac{q}{t}$

Therefore, $F = B\left(\frac{q}{t}\right)L\sin\theta \Rightarrow F = Bq\frac{L}{t}\sin\theta$

The term $\frac{L}{t}$ represents the velocity, v, of a moving charge because distance, L, traveled in time t is just velocity.

Substituting v in:

$F = Bqv\sin\theta$

Therefore:

$F = qvB\sin\theta$

where

F is the force (N)

q is the electric charge on the particle (C)

v is the component of the velocity of the particle that is perpendicular to the magnetic field ($m\,s^{-1}$)

B is the strength of the magnetic field (T)

θ is the angle between the particle and the magnetic field.

The $\sin\theta$ component of this equation comes from resolving a particle's velocity v into its parallel and perpendicular components. If you resolve the velocity of a positively charged particle, as in Figure 6.5.2, you will have two vector components. One of them will be perpendicular to the magnetic field, and one of them will be parallel to the field. The velocity component parallel to the field experiences no force, and so the entirety of the force acting on the particle is due to its velocity perpendicular to the field, $v_\perp$.

Using trigonometry, this perpendicular velocity can be written as $v\sin\theta$ (Figure 6.5.2). Thus, the total force acting is $F = qv_\perp B = qvB\sin\theta$. The direction of the force acting on a moving charged particle is given by the right-hand slap rule (Figure 6.5.3) in the same way as for currents in Module 6.4. With your thumb in the direction of motion of a positive charge and your fingers in the direction of the magnetic field, your palm will face the direction of the force. This direction is the opposite for a negatively charged particle. For the positively charged particle in Figure 6.5.2, using the right-hand slap rule with your thumb in the direction of the perpendicular velocity and fingers in the direction of the magnetic field, you see that the force on this charged particle is out of the page.

A charged particle travelling at a steady speed in a magnetic field experiences this force at an angle to its path and will be diverted.

This force is referred to as the **Lorentz force**. The force is at a maximum when the charged particle is moving at right angles to the field. There is no force acting when the charged particles are travelling parallel to the magnetic field or outside the magnetic field.

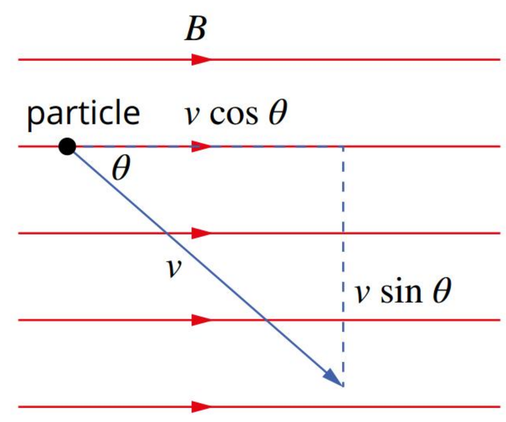


FIGURE 6.5.2 A particle travelling at an angle to a magnetic field can have its velocity vector resolved into parallel and perpendicular components.

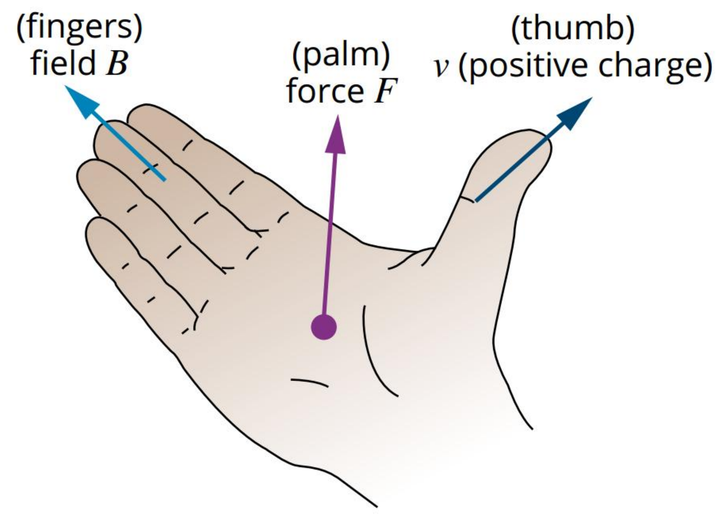
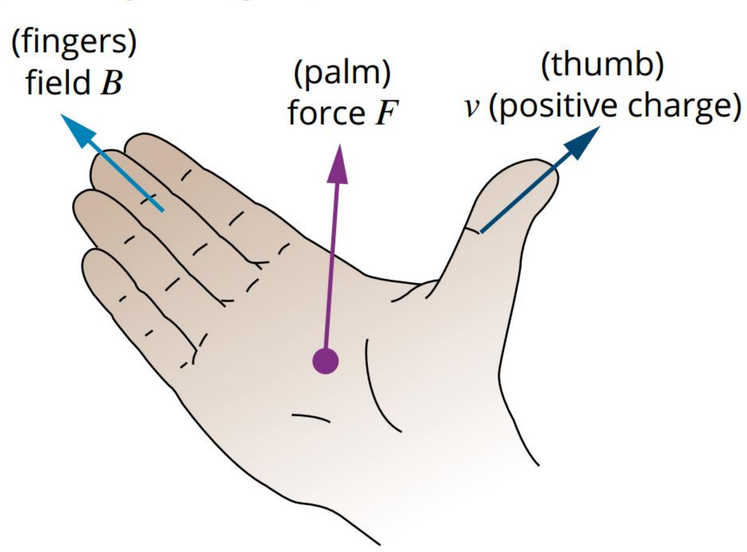


FIGURE 6.5.3 The right-hand slap rule: Point the thumb of the right hand in the direction of the movement of a positive charge (conventional current direction) and the fingers in the direction of the magnetic field. The force on the charge will point out from the palm.

Worked example 6.5.1

DIRECTION OF FORCE ON A NEGATIVELY CHARGED PARTICLE

A single, negatively charged particle with a charge of -1.6×10^{-19} C is travelling horizontally out of a computer screen and perpendicular to a magnetic field, B, that runs horizontally from left to right across the screen. Describe the direction in which the force experienced by the charge will act.

Thinking	Working
The right-hand slap rule is used to determine the direction of the force on a positively charged particle. 	Align your hand so that your fingers are pointing in the direction of the magnetic field, i.e. left to right and horizontal. If the negatively charged particle is travelling out of the screen, a positively charged particle would be moving in the opposite direction. Align your thumb so it is pointing into the screen, in the direction that a positive charge would travel. Your palm should be facing downwards. That is the direction of the force applied by the magnetic field on the negative charge out of the screen.

➤ Try yourself 6.5.1

DIRECTION OF FORCE ON A NEGATIVELY CHARGED PARTICLE

A single, negatively charged particle with a charge of -1.6×10^{-19} C is travelling horizontally from left to right across a computer screen and perpendicular to a magnetic field, B, that runs vertically down the screen. Describe the direction in which the force experienced by the charge will act.

Worked example 6.5.2

MAGNITUDE OF FORCE ON A POSITIVELY CHARGED PARTICLE

A single, positively charged particle with a charge of $+1.6 \times 10^{-19}$ C travels at a velocity of $10.0\,\text{m s}^{-1}$ perpendicular to a magnetic field, B, of strength 4.0×10^{-5} T.

Determine the magnitude of the force the particle will experience from the magnetic field.

Thinking	Working
Check the direction of the velocity and determine whether a force will apply. Forces only apply to the component of the velocity perpendicular to the magnetic field.	The particle is moving perpendicular to the field, so a force will apply: $F = qvB \sin\theta$
Establish which quantities are known and which ones are required.	$F = ?$ $q = +1.6 \times 10^{-19}$ C $v = 10\,\text{m s}^{-1}$ $B = 4.0 \times 10^{-5}$ T $\theta = 90°$
Substitute values into the force equation.	$F = qvB \sin 90°$ $= (1.6 \times 10^{-19}) \times 10 \times (4.0 \times 10^{-5})$
Express the final answer in an appropriate form. Note that only magnitude has been requested so do not include direction.	$F = 6.4 \times 10^{-23}$ N

➤ Try yourself 6.5.2

MAGNITUDE OF FORCE ON A POSITIVELY CHARGED PARTICLE

A single, positively charged particle with a charge of $+1.6 \times 10^{-19}$ C travels at a velocity of $50.0\,\text{m s}^{-1}$ perpendicular to a magnetic field, B, of strength 6.0×10^{-5} T.

Determine the magnitude of the force the particle will experience from the magnetic field.

Worked example 6.5.3

MAGNITUDE OF FORCE ON A POSITIVELY CHARGED PARTICLE AT AN ANGLE TO THE FIELD

A single, positively charged particle with a charge of $+1.6 \times 10^{-19}$ C travels at a velocity of $1.8 \times 10^{6}\,\text{m s}^{-1}$ at an angle of 60.0° to a magnetic field, B, of strength 3.5×10^{-3} T.

Calculate the magnitude of the force the particle will experience from the magnetic field.

Thinking	Working
Establish which quantities are known and which ones are required.	$F = ?$ $q = +1.6 \times 10^{-19}$ C $v = 1.8 \times 10^{6}\,\text{m s}^{-1}$ $B = 3.5 \times 10^{-3}$ T $\theta = 60.0°$

Substitute values into the force at an angle equation.	$F = qvB\sin\theta$ $= (1.6 \times 10^{-19}) \times (1.8 \times 10^{6}) \times (3.5 \times 10^{-3}) \times \sin 60.0°$
Express the final answer in an appropriate form. Note that only magnitude has been requested so do not include direction.	$F = 7.5 \times 10^{-16}\,\text{N}$

➤ Try yourself 6.5.3

MAGNITUDE OF FORCE ON A POSITIVELY CHARGED PARTICLE AT AN ANGLE TO THE FIELD

A single, positively charged particle with a charge of 3.2×10^{-19} C travels at a velocity of $2.3 \times 10^{4}\,\text{m s}^{-1}$ at an angle of 45° to a magnetic field, *B*, of strength 5.0 T.

Calculate the magnitude of the force the particle will experience from the magnetic field.

BEHAVIOUR OF CHARGED PARTICLES IN A MAGNETIC FIELD

Particle accelerators are machines that were originally designed to investigate the nature of matter by examining the structure of atoms and molecules. Charged particles, such as electrons, protons or atomic nuclei, are accelerated to speeds often close to that of light. These particles travel through an electric field, inside a hollow tube pumped to an ultra-high vacuum, with pressures comparable to those found in deep space. Strong magnets direct the particles to collide with a target or with another moving particle. Scientists obtain information about the make-up of the subatomic particles fired from the machine, or the target samples that are hit, by analysing the types of collisions that occur.

To explore the forces acting on a beam of electrons in a particle accelerator, the effect of a magnetic field on an individual charged particle needs to be considered. Recall from earlier in this module that the force on a charged particle moving perpendicularly through a magnetic field is $F = qvB$, with the direction given by the right-hand slap rule.

In the case of the magnetic force on an electron moving within the magnetic field of a particle accelerator, the magnitude of charge, q, is equal to 1.6×10^{-19} C. Note that as this is a negatively charged particle, the direction of the force will be reversed; the right-hand slap rule uses conventional current rather than electron flow.

If a moving charge experiences a force of constant magnitude that remains at right angles to its motion, its direction will be changed but not its speed. In this way, bending magnets within a particle accelerator act to alter the path of the electron beam (Figure 6.5.4), rather than to speed the electrons up. As a result, the electrons will follow a curved path of radius r.

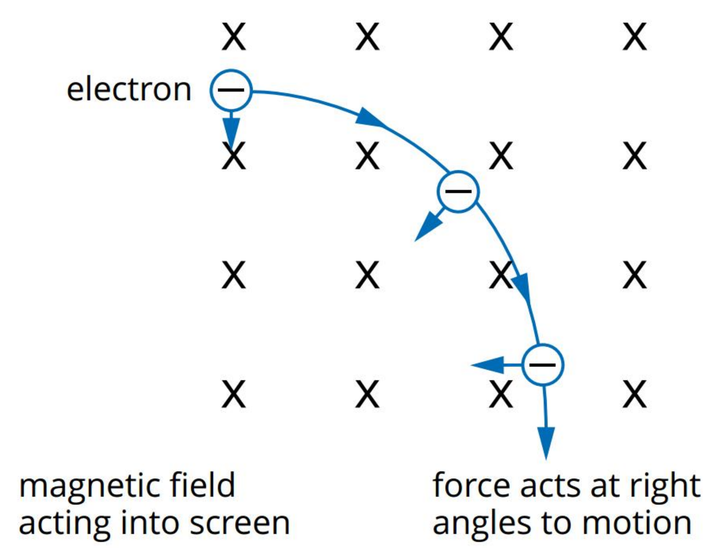


FIGURE 6.5.4 An electron moving in a magnetic field.

In this case, the net force acting on the charge is:

$$F = ma$$

This is equivalent to the magnetic force on the charge, so that:

$$qvB = ma$$

The acceleration in this situation is centripetal (towards the centre of the circular path) and has magnitude:

$$a_c = \frac{v^2}{r}$$

Substituting this relationship into the previous equation gives:

$$qvB = \frac{mv^2}{r}$$

Rearranging this equation gives an expression that predicts the radius of the path of an electron travelling at right angles to a constant magnetic field:

$$r = \frac{mv}{qB}$$

where

r is the radius of the path (m)

m is the mass of the electron (9.109×10^{-31} kg)

v is the speed of the electron ($\mathrm{m\,s^{-1}}$)

q is the charge on the electron (-1.60×10^{-19} C)

B is the strength of the magnetic field (T).

This relationship can be used to calculate the radius of the path followed by an electron travelling at right angles to any magnetic field. The electron could be a low-velocity electron or could be a high-velocity electron that has been accelerated by the powerful bending magnets within a particle accelerator. Further, the relationship can be used to calculate the radius of any charged particle—positive or negative—travelling at right angles to a magnetic field.

Worked example 6.5.4

CALCULATING SPEED AND PATH RADIUS OF ACCELERATED CHARGED PARTICLES

An electron gun (a device to accelerate electrons) releases electrons and accelerates them across a potential difference of 32 kV over a distance of 30.0 cm between a pair of charged parallel plates. Assume that the mass of an electron is 9.109×10^{-31} kg and the magnitude of the charge on an electron is 1.60×10^{-19} C.	
a Calculate the strength of the electric field acting on the electron beam.	
Thinking	**Working**
Ensure that the variables are in their standard units.	$32\,\mathrm{kV} = 32 \times 10^3 = 3.2 \times 10^4\,\mathrm{V}$ $30\,\mathrm{cm} = 0.30\,\mathrm{m}$
Recall the equations for potential difference and the strength of the electric field from Chapter 5.	$V = \frac{\Delta U}{q}$ $E = \frac{F}{Q}$
Given a reference point at infinity, the change in potential energy is equal to the work done.	$V = \frac{W}{q}$
Recall from *Pearson Physics 11 Queensland* that the work is equal to the force over a distance (here given the variable d).	$W = Fd$
Derive an equation that utilises the known variables of E, V and d.	$V = \frac{W}{q} = \frac{Fd}{q} = \frac{Eqd}{q}$ $\therefore V = Ed$ Or $E = \frac{V}{d}$
Solve for E.	$E = \frac{3.2 \times 10^4}{0.30}$ $= 1.1 \times 10^5\,\mathrm{V\,m^{-1}}$

b Calculate the speed of the electrons as they exit the electron gun.	
Thinking	**Working**
Recall from *Pearson Physics Queensland Units 1 & 2*, the equation for kinetic energy. Recall from Chapter 5 the equation for the change in potential difference of a charge in an electric field.	$E_k = \frac{1}{2}mv^2$ $V = \frac{\Delta U}{q}$ Rearrange the second equation to make ΔU the subject. $\Delta U = qV$
According to the law of conservation of energy, the change in potential energy will be equal to the change in kinetic energy.	$\Delta E_k = \Delta U$
Substitute the equations for E_k and ΔU.	$\frac{1}{2}mv^2 = qV$
Rearrange the equation to make v the subject and solve for v.	$v = \sqrt{\frac{2qV}{m}}$ $= \sqrt{\frac{2 \times (1.60 \times 10^{-19}) \times (3.2 \times 10^4)}{9.109 \times 10^{-31}}}$ $= 1.06 \times 10^8\,\text{m s}^{-1}$
c The electrons then travel through a uniform magnetic field perpendicular to their motion. Given that the strength of this field is 0.20 T, calculate the expected radius of the path of the electron beam.	
Thinking	**Working**
Recall the equation for the net force.	$F = ma$
The net force is equivalent to the magnetic force on the charge.	$qvB = ma$
The acceleration in this situation is circular so the equation for centripetal acceleration can be used.	$a = \frac{v^2}{r}$
Substitute this into the previous equation.	$qvB = \frac{mv^2}{r}$
Simplify the previous equation.	$r = \frac{mv}{qB}$
Solve for r.	$= \frac{(9.109 \times 10^{-31}) \times (1.06 \times 10^8)}{1.60 \times 10^{-19} \times 0.2}$ $= 3.0 \times 10^{-3}\,\text{m}$

➤ Try yourself 6.5.4

CALCULATING SPEED AND PATH RADIUS OF ACCELERATED CHARGED PARTICLES

An electron gun releases electrons and accelerates them across a potential difference of 25 kV over a distance of 20.0 cm between a pair of charged parallel plates. Assume that the mass of an electron is 9.109×10^{-31} kg and the magnitude of the charge on an electron is 1.60×10^{-19} C.

a Calculate the strength of the electric field acting on the electron beam.

b Calculate the speed of the electrons as they exit the electron gun.

c The electrons then travel through a uniform magnetic field perpendicular to their motion. Calculate the expected radius of the path of the electron beam given that the strength of this field is 0.30 T.

Deflection of alpha, beta and gamma radiation in a magnetic field

In Year 11 you learnt about different types of radiation: alpha particles, beta particles and gamma rays. Alpha particles, the strongly positively charged nuclei of helium atoms, will be deflected in a magnetic field. The right-hand slap rule is used to determine the direction. Beta particles can be positively or negatively charged and so the direction of this force depends on the charge that they carry. Gamma rays, the high-energy beams of light that are emitted in certain nuclear reactions, are uncharged and so will pass through a magnetic field without deflection.

We can calculate the difference in the effect on alpha and beta particles in a magnetic field by determining their path radii. Alpha particles have an approximate mass of 6.64×10^{-27} kg and a charge of $2 \times 1.602 \times 10^{-19}$ C. The path radius of alpha particles at a speed of $1.5 \times 10^{6}\,\mathrm{m\,s^{-1}}$ in a magnetic field of 1.0 T is:

$$r_\alpha = \frac{mv}{qB} = \frac{(6.64 \times 10^{-27}) \times (1.5 \times 10^{6})}{2 \times 1.602 \times 10^{-19} \times 1.0} = 0.031\,\mathrm{m}$$

Similarly, a beta particle has a mass of 9.11×10^{-31} kg and a charge magnitude of 1.602×10^{-19} C. At the same speed in the same field, its path radius is:

$$r_\beta = \frac{mv}{qB} = \frac{(9.11 \times 10^{-31}) \times (1.5 \times 10^{6})}{(1.602 \times 10^{-19}) \times 1.0} = 8.5 \times 10^{-6}\,\mathrm{m}$$

It is clear that the lower mass of the beta particles results in a much smaller path radius for these particles. This is the reason why many early particle accelerators dealt with collisions of electrons rather than heavier particles like protons. It requires far less powerful magnets to keep beta particles at a high velocity within a given path radius. It was only in 1971 that CERN unveiled the world's first proton–proton collider, the Intersecting Storage Rings.

The different paths of alpha, beta and gamma radiation in a magnetic field are summarised in Figure 6.5.5.

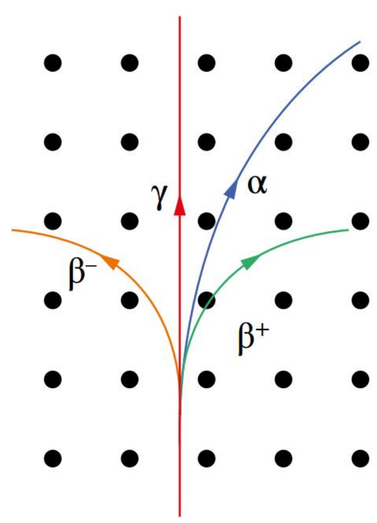


FIGURE 6.5.5 The paths of different types of radiation in a magnetic field. Using the right-hand slap rule, you see that positively charged particles are forced to the right. Alpha (α) particles are much heavier than beta particles, and so are deflected less. Beta minus (β^-) is deflected the same amount as beta plus (β^+), but in the opposite direction. Gamma (γ) rays are uncharged and so pass straight through.

Magnetism and relativity

Magnetism is not as straightforward as it might seem! There are some subtle connections between magnetism, electrostatics, and special relativity that make it even more intriguing. As discussed earlier, the magnetic fields around two parallel current-carrying wires interact in the same way as the fields of two bar magnets. However, consider the perspective of an electron in one of the wires. From its point of view, it appears stationary, as do the electrons in the second wire (assuming the same current flows). This seems contradictory—magnetic fields are created by moving charged particles, yet from this viewpoint, the charges are not moving at all. So what is the explanation?

A force must exist in all frames of reference, and according to Einstein, no single perspective holds special significance. At the beginning of the 20th century, this was

one of the great unsolved mysteries of physics. The answer, as you will explore in Chapter 8, lies in the special theory of relativity.

Now, consider two stationary charges, A and B, positioned close to each other. They experience the electrostatic force described in Chapter 5. But if the frame of reference shifts so that A and B are moving, they each carry both an electric field and a magnetic field, interacting in a new way. This leads to a key idea in modern physics: electric and magnetic fields are not separate entities but rather different aspects of a single electromagnetic field.

6.5 Review

SUMMARY

- The magnitude of the force on a charged object within a magnetic field is proportional to the strength of the magnetic field, B, the component of the velocity of the charge that is perpendicular (at right angles) to the magnetic field, and the charge on the particle.
- This force is referred to as the Lorentz force.
- When the velocity is at an angle to the field, the force on a charged particle is $F = qvB\sin\theta$.
- The force is at a maximum when the charged particle is moving perpendicular to the magnetic field.
- The force is zero when the charged particle is travelling parallel to the magnetic field.
- The right-hand slap rule is used to determine the direction of the force on a positive charge moving in a magnetic field, B. The direction of the force on a negatively charged particle is in the opposite direction.
- Particle accelerators are machines that accelerate charged particles, such as electrons, protons and atomic nuclei, to speeds close to that of light.
- The equations for centripetal acceleration and magnetic force can be combined to find the radius of the path of a charged particle travelling at right angles to a uniform magnetic field is given by $r = \frac{mv}{qB}$.
- The equation for kinetic and potential energy can be combined to find the velocity of a charged particle accelerated within a potential difference: $v = \sqrt{\frac{2qV}{m}}$.

KEY QUESTIONS

Describe

1 State the equation for the Lorentz force for a charged particle travelling perpendicularly to a magnetic field and what each quantity represents.

2 Identify the force acting on a particle if the velocity is parallel to the magnetic field.

3 State how the force acting on a particle changes if the velocity is tripled.

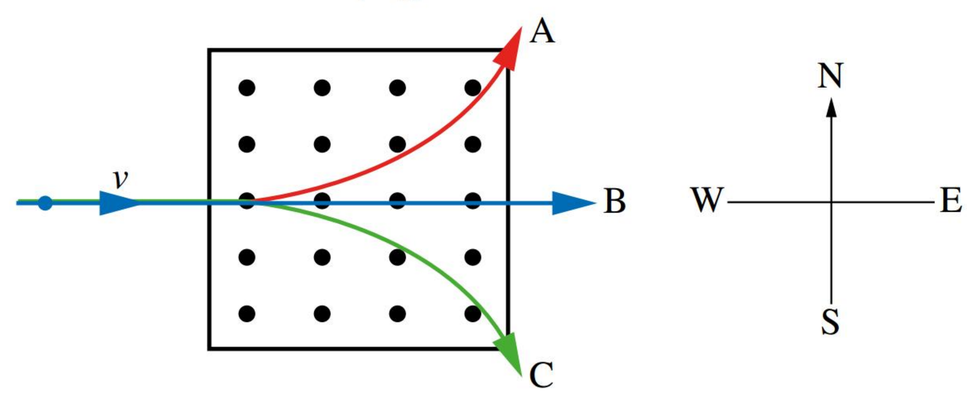
Apply

4 Identify how the radius of a curved path changes when the velocity of the particle is doubled.

5 State the direction in which a charged particle will move if there is no magnetic field present. Explain your reasoning.

6 Explain why the force on a particle travelling at an angle θ to a magnetic field is $qvB\sin\theta$ rather than $qvB\cos\theta$.

7 The following diagram shows a particle, with initial velocity v, about to enter a uniform magnetic field, B, directed out of the page.



a State the direction of the force just as the particle enters the field if the particle is positively charged.

b Describe the path this particle will follow.

c Identify whether the kinetic energy of the particle increases, decreases or remains constant.

d Identify the path a negatively charged particle would follow.

e Determine the kind of particle that could follow path B.

6.5 Review *continued*

8 Explain how particle accelerators can use electromagnetic fields to provide the centripetal acceleration to change the direction of a charged particle.

Analyse

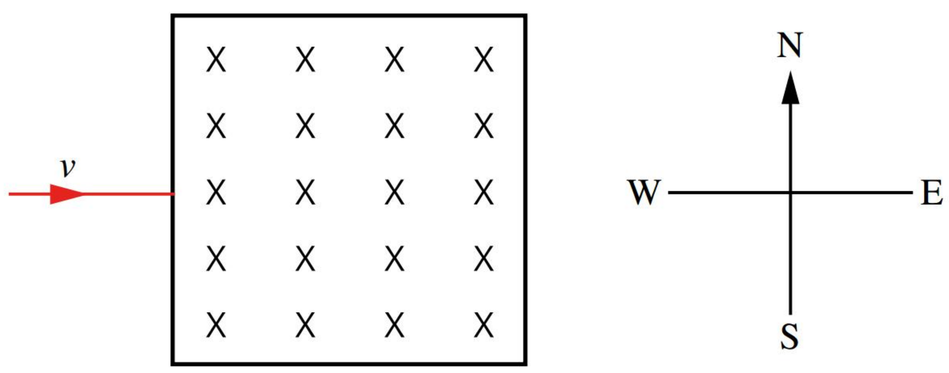
9 Calculate the magnitude of the force acting on an electron with charge -1.600×10^{19} C as it enters a magnetic field of strength 2.0×10^{-3} T at a velocity of $1.5\,\text{m s}^{-1}$ perpendicular to the field.

10 A single, positively charged particle with a charge of -1.6×10^{-19} C enters a magnetic field of strength 3.2×10^{-5} T at an angle of 45 and experiences a force of 4.3×10^{-23} N. Calculate the velocity of the charge.

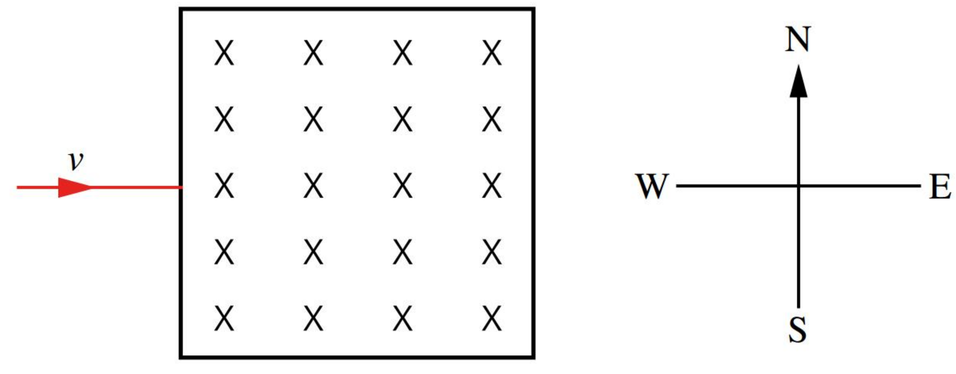
11 An electron with a charge of -1.60×10^{-19} C is moving eastwards into a magnetic field of strength $B = 1.5 \times 10^{-5}$ T acting in a north-easterly direction. Calculate the magnitude and direction of the force it initially experiences as it enters the magnetic field if the magnitude of the initial velocity is $1.0\,\text{m s}^{-1}$.

12 An electron with speed $7.6 \times 10^{6}\,\text{m s}^{-1}$ travels through a uniform magnetic field and follows a circular path of diameter 9.2×10^{-2} m. Calculate the magnetic field strength through which the electron travels.

13 An electron with a charge of -1.60×10^{-19} C is moving eastwards into a magnetic field of strength 1.5×10^{-5} T, acting into the page, as shown below. Determine the magnitude and direction of the force the electron initially experiences as it enters the magnetic field if the magnitude of the initial velocity is $2.0 \times 10^{7}\,\text{m s}^{-1}$.



14 An alpha particle with a charge of $+3.2 \times 10^{-19}$ C is moving eastwards into a magnetic field acting into the page, as shown below. The force it experiences is *F*. Determine the magnitude and direction of the magnetic force it would experience in terms of *F* if the velocity, *v*, of the particle is doubled.



15 Tristen is studying the tracks left by an unknown particle travelling in a magnetic field. Using a variety of techniques, he calculates the mass to be 2.03×10^{-26} kg. He then sends the particle at a velocity of $1.80 \times 10^{8}\,\text{m s}^{-1}$ through a 2.0 T magnetic field at an angle of 35°. Determine the charge of the particle if the acceleration of the particle is detected to be $4.88 \times 10^{15}\,\text{m s}^{-1}$.

Chapter review

06

KEY TERMS

dipolar
dipole
electromagnet
ferromagnetic materials
Lorentz force
magnetic
magnetic field
magnetic field lines
magnetic force
magnetic pole
magnetism
permanent magnet
permeability of a vacuum
pole
right-hand grip rule
right-hand slap rule
solenoid
temporary magnet

KEY QUESTIONS

Describe

1 Select the correct statement relating to magnetic poles.

A Opposite poles attract; like poles repel.
B Opposite poles repel; like poles attract.

2 Identify the best option to complete the sentence. The magnitude of the magnetic force on a conductor aligned so that the current is running parallel to a magnetic field is:

A zero
B a maximum
C dependent on the size of the current
D dependent on the length of the conductor

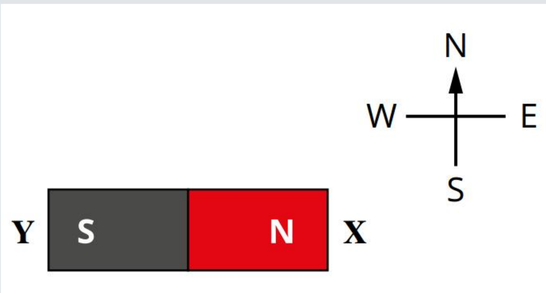
3 The right-hand slap rule is used to determine the force on a current-carrying conductor perpendicular to a magnetic field. Recall what part of the hand corresponds to the following physical quantities:

a magnetic force
b magnetic field
c current in the conductor.

4 Describe the magnetic field produced for a positive charge moving west.

5 Describe why a magnetic field is a vector quantity.

6 Identify the direction of the magnetic field at points X and Y in the following diagram.



A X: East Y: East
B X: West Y: West
C X: South Y: North
D X: North Y: South

Apply

7 Two bar magnets are placed so that the resultant field between the two is equal to zero. Sketch the magnetic field lines for this scenario.

8 Identify the correct statement about the magnetic field strength in a solenoid. The magnetic field at a point well inside a solenoid is:

A uniform and dependent on the radius of the solenoid
B uniform and independent on the radius of the solenoid
C non-uniform and dependent on the radius of the solenoid
D non-uniform and independent on the radius of the solenoid

9 Sketch the magnetic field lines between:

a two like poles
b two opposite poles.

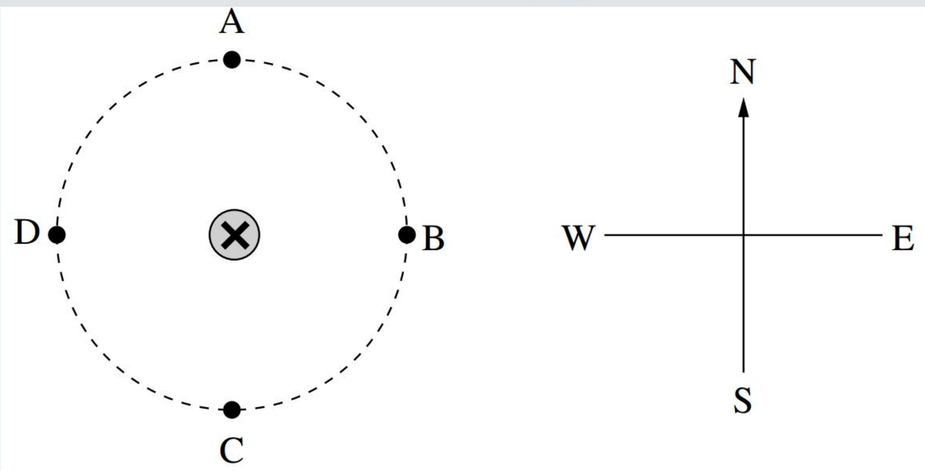
10 Determine the magnetic field strength produced by a 30.0 cm solenoid with 20 turns carrying a current of 5.0 A.

A 1.2×10^{-6} T
B 4.2×10^{-6} T
C 1.2×10^{-4} T
D 4.2×10^{-4} T

11 Describe how the magnetic fields of two current-carrying wires parallel to each other interact when the current in both wires is running in the same direction.

The following diagrams relate to questions **12–14**.

The figure below shows a cross-sectional view of a long, straight, current-carrying conductor, with its axis perpendicular to the plane of the page. The conductor carries an electric current into the page.



12 Determine the direction of the magnetic field produced by this conductor at point B.

13 Describe the direction of the magnetic field produced at point D if the current through the conductor is doubled.

14 Describe the direction of the magnetic field produced at point A if the direction of the current is reversed and halved.

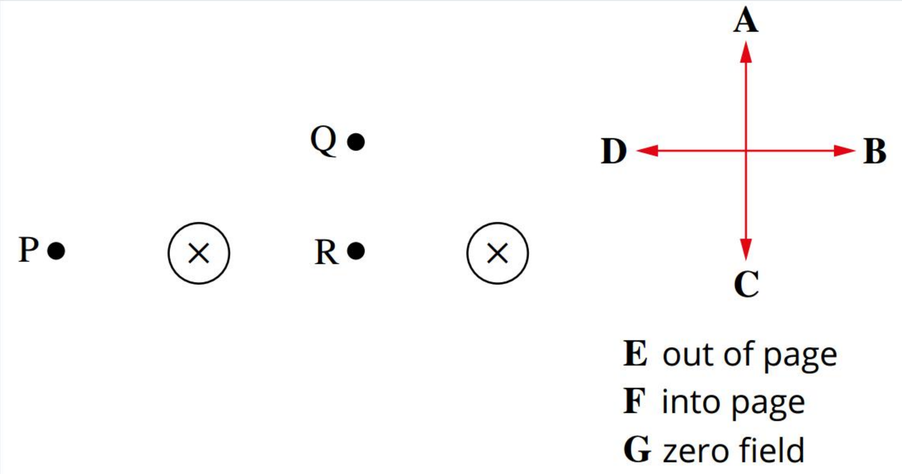
15 The following diagrams show two different electron beams being bent as they pass through two different regions of a uniform magnetic field of equal magnitudes B_x and B_y. The initial velocities of the electrons in the respective beams are v_1 and v_2. Select the correct term from those in **bold**, to complete the sentence.

For the electron beams to behave as shown in **a**, v_1 is **equal to / less than** v_2 and the region of the magnetic field, B_y, must be acting **out of / into** the page.

16 A horseshoe magnet is held vertically with the north pole of the magnet on the left and the south pole of the magnet on the right.

Describe the direction of the magnetic force acting on a wire passing between the poles.

17 The left diagram below represents two conductors, both perpendicular to the page and both carrying equal currents into the page (shown by the crosses in the circles). Ignore any contribution from Earth's magnetic field. Choose the correct options from the arrows A–D and letters E–G.



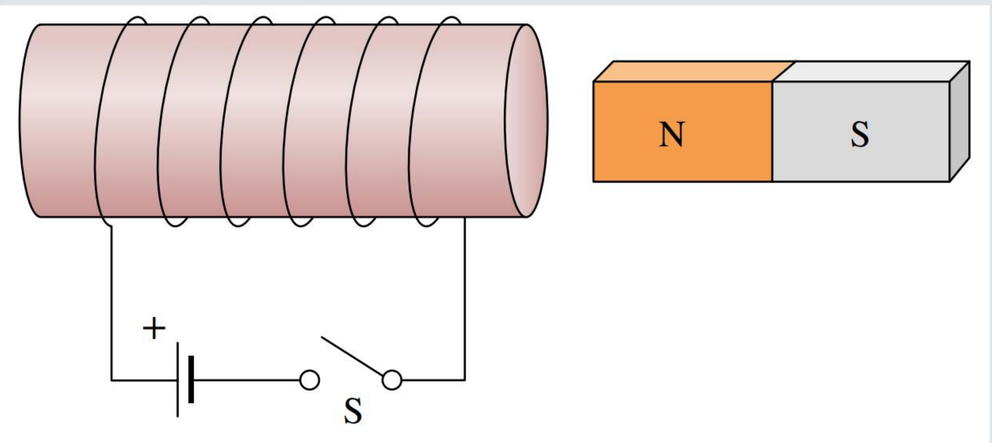
Determine the direction of the magnetic field due to the two currents at each of the following points:

a point P

b point Q

c point R.

18 An electromagnet with a soft iron core is set up as shown in the diagram below. A small bar magnet with its north end towards the electromagnet is placed to the right of it. The switch S is initially open. The following questions refer to the force between the electromagnet and the bar magnet under different conditions.

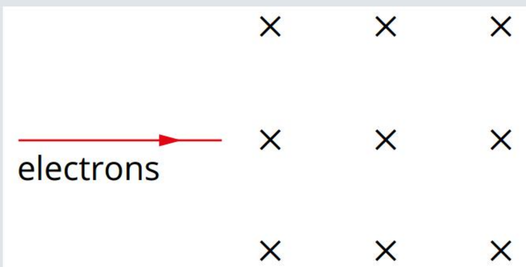


a Describe the force on the bar magnet while the switch remains open.

b Describe the force on the bar magnet when the switch is closed and a large current flows.

c The battery is removed and then replaced so that the current flows in the opposite direction. Describe the force on the bar magnet now when the switch is closed.

19 This diagram shows a stream of electrons entering a magnetic field. Draw the diagram and show the subsequent path of the electrons through the magnetic field.



Analyse

20 A student sets up an experiment to analyse the force acting on a conductor in a magnetic field. They graph their results of the current through the conductor against the observed force. What shape do you expect their graph to take?

A positive linear
B negative linear
C parabolic
D inverse square

21 A student is conducting an experiment to analyse the strength of a magnet at various distances. Using a magnetometer, they collect the following data:

	Distance (cm)	Magnetic field strength ($\times 10^{-3}$ T)				
		Trial 1	Trial 2	Trial 3	Average B ($\times 10^{-3}$ T)	ΔB ($\times 10^{-3}$ T)
A	20	3.5	3.4	3.6	3.5	0.1
B	30	2.8	2.7	2.6	2.7	0.1
C	40	1.5	1.4	1.6	1.5	0.1
D	50	0.7	0.8	0.8	0.77	0.05

Identify which row contains an error in the magnetic field strength uncertainty.

The following information relates to questions **22–24**.

A solenoid carrying a current of 10.0 A produces a magnetic field of 6.0×10^{-4} T.

22 Determine the resulting magnetic field strength if the current is increased to 40.0 A and the number of turns per unit length is reduced by a factor of two.

23 Determine the resulting magnetic field strength if the current is decreased to 5.0 A and the number of turns per unit length is reduced by a factor of two.

24 Calculate by how much the current required to generate the magnetic field would be reduced if the magnetic field remains the same and the number of turns was increased by a factor of 10.

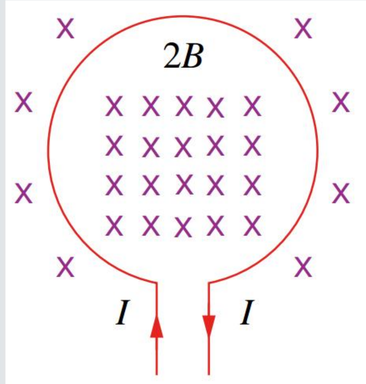
25 A current-carrying wire runs horizontally across a table. The conventional current direction, I, is running from right to left. The wire produces a magnetic field of 2.0×10^{-6} T measured 10.0 cm from the wire.

a Calculate the current the wire must be carrying to produce that field.

b Draw a diagram showing the direction of the magnetic field around the wire.

The following information relates to questions **26–28**.

The diagram below shows a loop carrying a current, I, that produces a magnetic field of magnitude B in the centre of the loop. Its direction is not shown in the diagram. The loop is placed into a region where there is already a steady field of magnitude B (the same magnitude as that due to I) directed into the page. The resultant magnetic field inside the loop has a magnitude of $2B$.



26 Calculate the magnitude and direction of the resultant field at the centre of the loop if the current in the loop is switched off.

27 Calculate the magnitude and direction of the resultant field at the centre of the loop if the current in the loop is doubled.

28 Calculate the magnitude and direction of the resultant field at the centre of the loop if the current in the loop is reversed but maintained at the same magnitude.

29 Calculate the magnitude and direction of the magnetic force on conductors with the following sets of data.

a $B = 1.0$ mT left, $L = 5.0$ mm, $I = 1.0$ mA up.

b $B = 0.10$ T down, $L = 1.0$ cm, $I = 2.0$ A into the page.

30 **a** Calculate the magnitude of the force exerted on a proton (mass = 1.673×10^{-27} kg) travelling at speed of 6.4×10^{6} m s^{-1} at right angles to a uniform magnetic field of strength 9.1×10^{-3} T.

b Calculate the radius of its orbit, given that this force directs the electron in a circular path.

31 A student is testing the strength of a magnetic field around a magnet using a magnetometer app on their phone. They collect the following data:

Distance (cm) ± 1.0 cm	Magnetic field strength (μT)			
	Trial 1	Trial 2	Trial 3	Average
5	6400	6410	6404	
10	2001	2004	2004	2003
15	523	529	532	528
20	101	104	109	105
25	63	61	60	61
30	39	33	30	34
35	27	24	26	26
40	17	15	13	15

a Create a graph of the dependent and independent variables of the experiment.

b Identify the relationship found in part **a**.

32 A student sets up an experiment to test the magnetic force on a current-carrying wire for various currents. They use two bar magnets aligned so that a magnetic field acts perpendicularly to a conducting wire. They place a measuring scale under the setup and observe the values of the mass for each current.

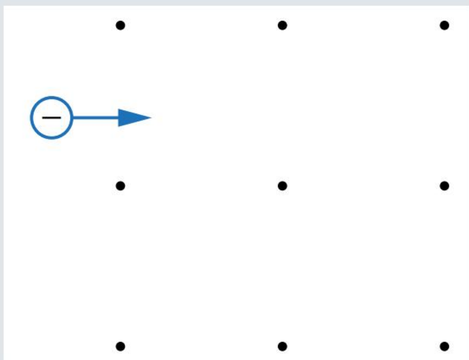
By measuring the weight force for each current and using the third law of motion, they are able to calculate the magnetic force acting on the wire.

They collect the following data.

Current (A)	Mass (g)	Magnetic force ($\times 10^{-4}$ N)
0.5	0.09	
1.0	0.19	
1.5	0.28	
2.0	0.38	
2.5	0.47	
3.0	0.56	

Create a graph of the independent and dependent variables of the investigation. Comment on the relationship found between these two variables.

33 The diagram below represents an electron being fired at right angles towards a uniform magnetic field acting out of the page.

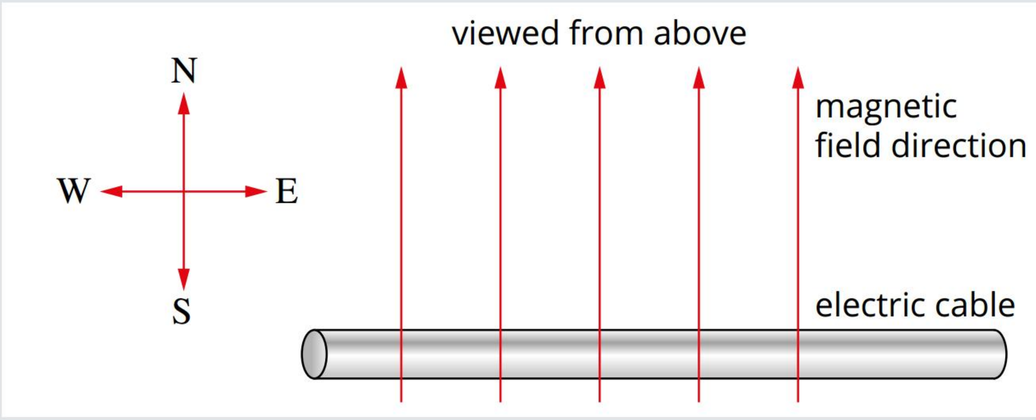


a Show the continued path of the electron on a copy of the diagram.

b Consider the factors that would alter the path radius of the electron as it travels.

The following information applies to questions **34–38**.

The diagram below shows a horizontal, east–west electric cable located in a region where Earth's magnetic field is horizontal and has a magnitude of 1.0×10^{-5} T. The cable has a mass of 0.050 kg m^{-1}.



34 Determine the magnitude of the magnetic force on a 1.0 m section of this cable if a 100.0 A current is flowing through it.

35 Determine the direction of the current that will produce a force on this cable out of the page.

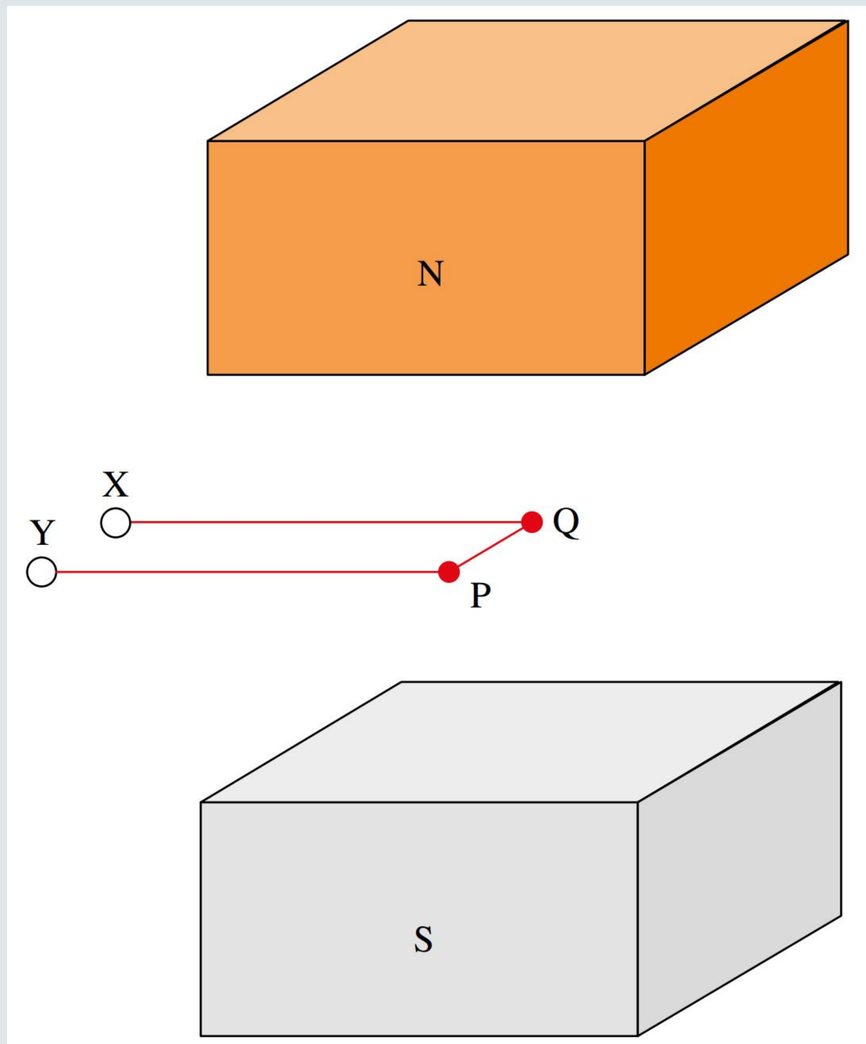
36 Calculate the magnitude of current required to produce zero resultant vertical force on a 1.0 m section of this cable. Use $g = 9.8\,\text{m s}^{-2}$.

37 Determine the change in magnetic force per metre on this cable if the direction of this current is reversed. Assume that a 100.0 A current is flowing through this cable from west to east.

38 The cable now makes an angle of 30.0° with the direction of Earth's magnetic field. Calculate the force that a 100.0 A current passing through this cable would produce.

The following information relates to questions **39–41**.

The following diagram shows a section of a conducting loop XQPY, part of which is placed between the poles of a magnet whose uniform field strength is 1.0 T. The side PQ has length 5.0 cm. X is connected to the positive terminal of a battery while Y is connected to the negative terminal. A current of 1.0 A then flows through this loop.



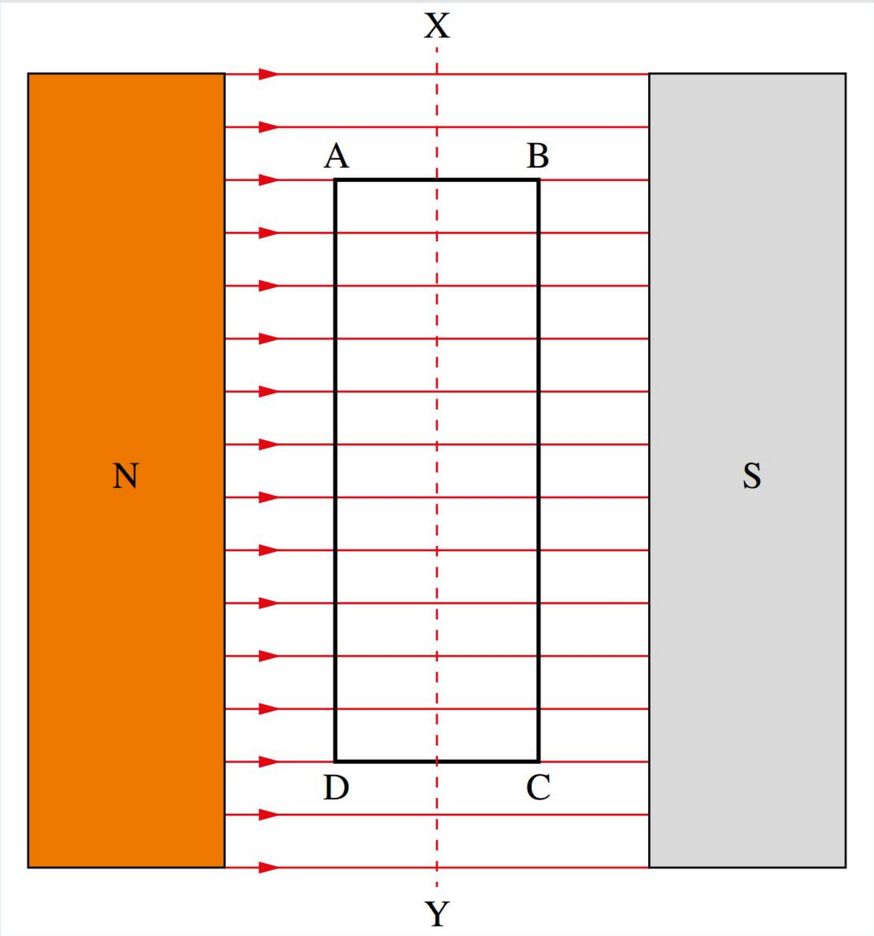
39 Calculate the magnitude of the force on side PQ.

40 Determine the direction of the force on side PQ.

41 Determine the magnitude of the force on a 1.0 cm section of side XQ that is located in the magnetic field.

The following information relates to questions **42–43**.

A rectangular coil containing exactly 100 turns and of dimensions 10.0 cm × 5.0 cm is located in a magnetic field $B = 0.25\,T$, as shown. It is free to rotate about the axis XY. The coil carries a constant current $I = 200.0\,mA$ flowing in the direction ADCB.



42 Determine the magnitude and direction of the magnetic force on sides:

a AB

b DC.

43 Determine the magnitude and direction of the magnetic force on sides:

a AD

b BC.

44 A rectangular loop of exactly 100 turns is suspended in a magnetic field $B = 0.50\,T$. The plane of the loop is parallel to the direction of the field. The dimensions of the loop are 20.0 cm perpendicular to the field lines and 10.0 cm parallel to them.

a It is found that there is a force of 40.0 N on each of the sides perpendicular to the field. Calculate the current in each turn of the loop.

b This loop is then replaced by a square loop of side length 10.0 cm, with twice the current and half the number of turns. Determine the force on each of the perpendicular sides now.

c The original rectangular loop with the original current is returned but a new magnet is used that provides a field strength of 0.80 T. Determine the force on the 20.0 cm side now.

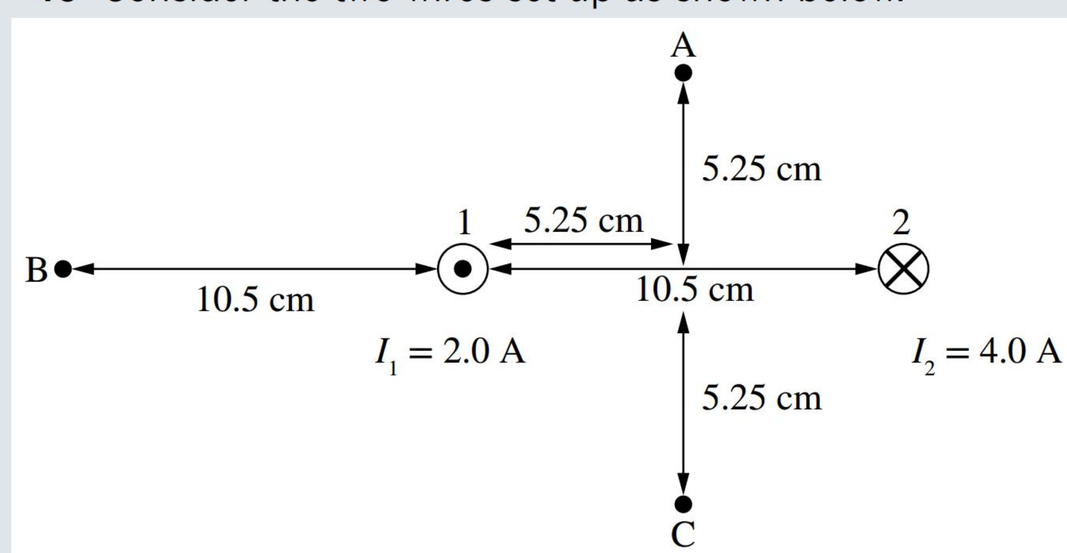
Interpret

45 A 45 cm solenoid with 200 turns is connected to 5 A of current from a power source. The magnetic field strength at various distances from the solenoid is observed using a gaussmeter.

Distance (cm)	Magnetic field strength (μT)			
	Trial 1	Trial 2	Trial 3	Average
5	2795	2793	2792	2793.33
10	1240	1244	1241	1241.67
15	587	583	588	586.00
20	304	307	300	303.67
25	139	136	136	
30	62	60	61	61.00
35	45	42	43	43.33
40	43	40	42	41.67
45	41	40	41	40.67

Interpret the shape of the graph that is produced of the magnetic field strength versus distance for the solenoid. Comment on the maximum and minimum values of the magnetic field strength as seen in the graph.

46 Consider the two wires set up as shown below.

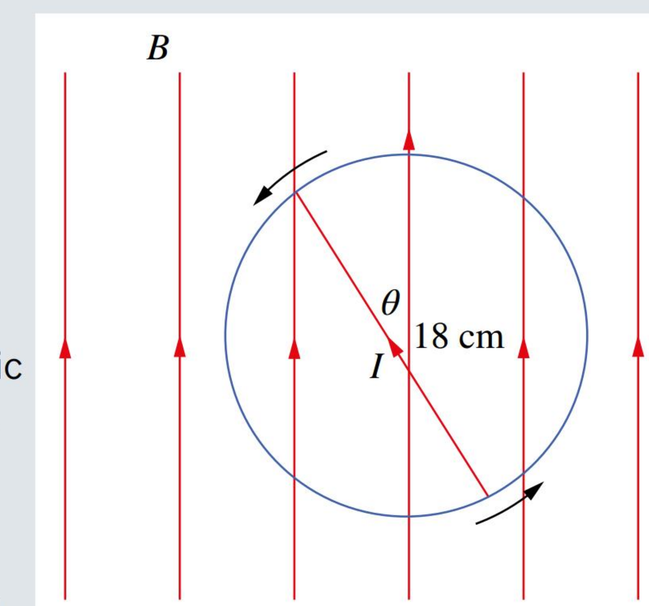


a Determine the direction of the magnetic field due to wire 1 at points A, B and C.

b Determine the direction of the magnetic field due to wire 2 at points A, B and C.

c Calculate the net magnetic field strength and direction at points A, B and C.

47 Natalie decides to set up an experiment to test the angular dependence of the force on a current-carrying wire in a magnetic field. To this end, she sets up a wire on a wheel as shown below. Consider the rest of the wire to be directed into the table and unaffected by the magnetic field. She takes measurements of the force acting on the wire as it rotates from 0 to 360°. The wire is carrying a current of 4.0 A and is 18 cm long. Generate a sketch of the force versus angle graph for a magnetic field of 0.500 mT, taking the initial force direction to be positive.

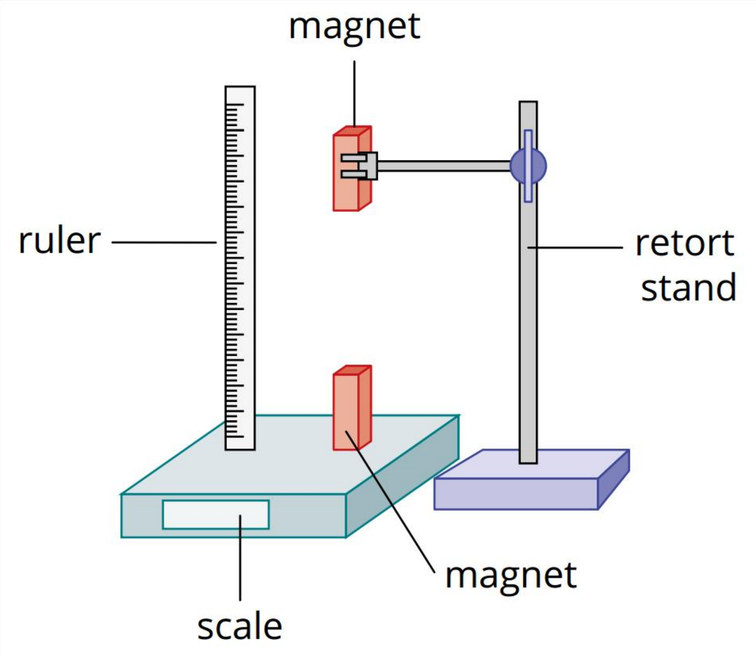


Data analysis

DATA SET 1

The information below applies to Questions **1**–**3**.

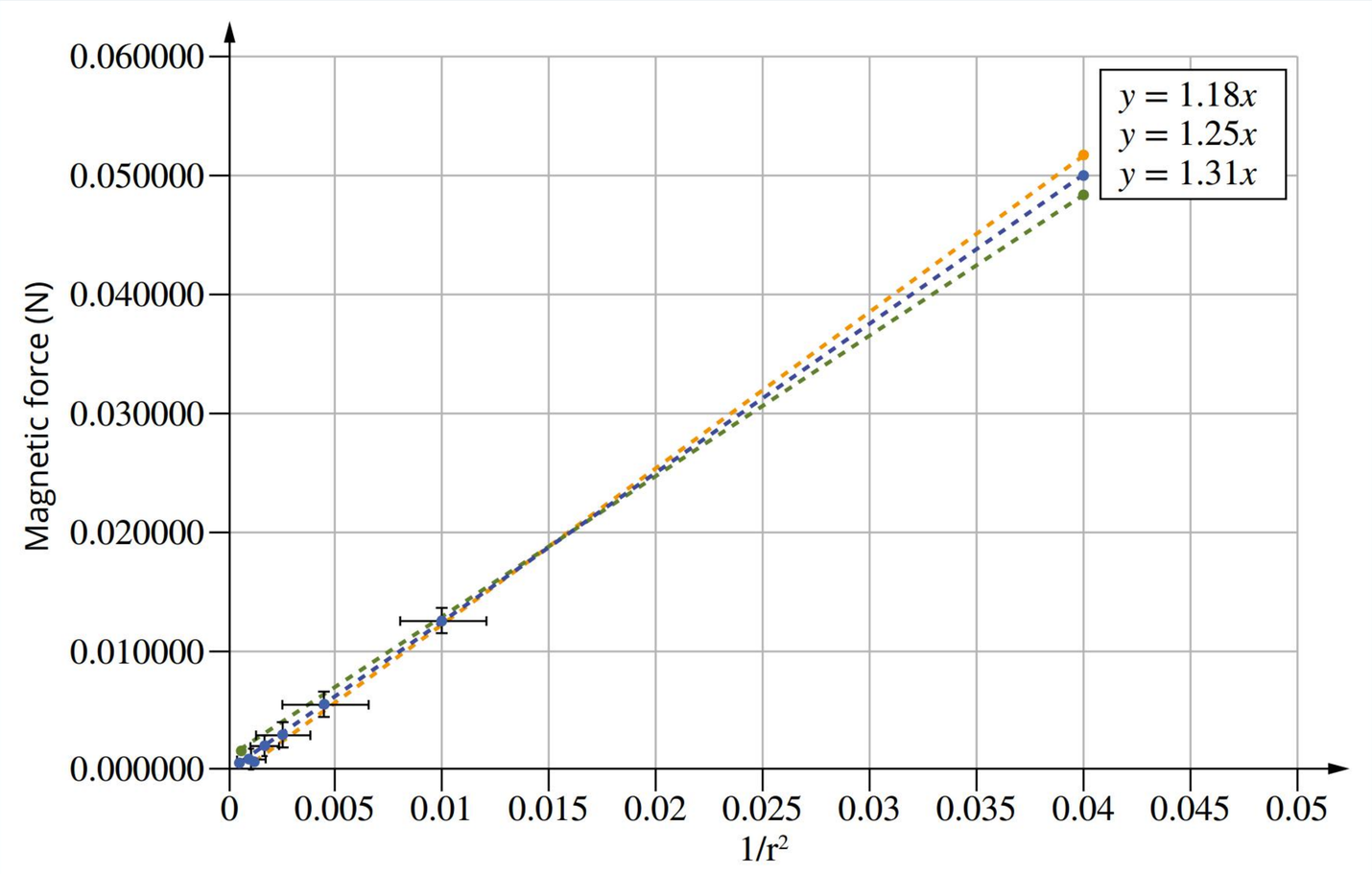
A student wants to test the force of attraction between two bar magnets separated at various distances. They setup their experiment as follows:



They first tare the scale so that it reads zero when the first magnet is placed on it. Then, by moving one of the magnets every 5 cm, they observe the mass on the scale and take the following measurements.

Distance between magnets (cm)	Mass (g)				Magnetic force (N)
	Trial 1	Trial 2	Trial 3	Average	
45	0.06	0.05	0.06	0.06	0.000 555
40	0.08	0.07	0.08	0.08	0.000 751
35	0.1	0.11	0.09	0.10	0.000 980
30	0.15	0.14	0.16	0.15	0.001 470
25	0.2	0.21	0.22	0.21	0.002 058
20	0.32	0.3	0.31	0.31	0.003 038
15	0.58	0.56	0.55	0.56	0.005 521
10	1.27	1.28	1.29		
5	5.1	5	5.2	5.10	0.049 980

They produce the following graph after linearising the data.



Question 1 (1 marks)

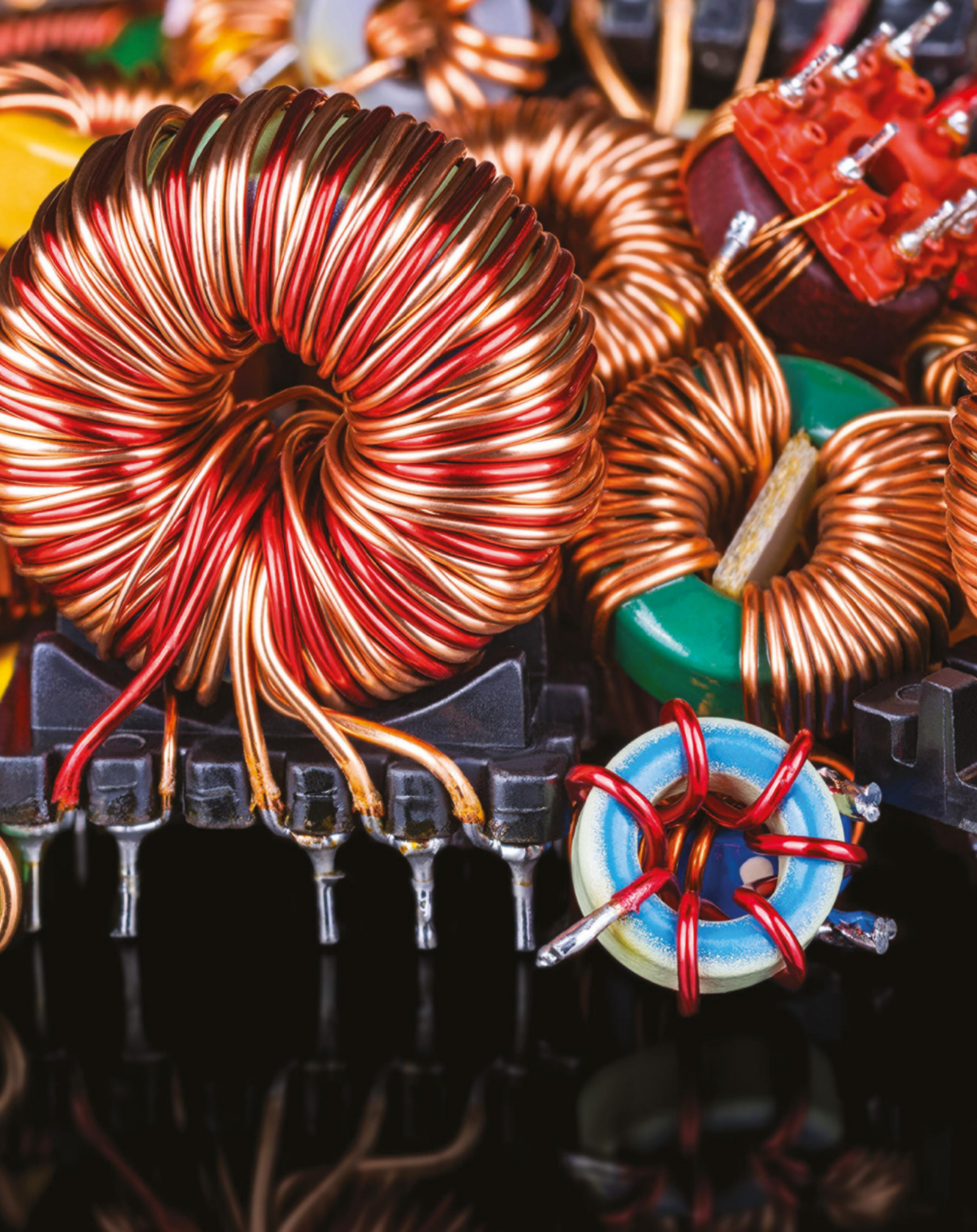
Calculate the missing average in the table.

Question 2 (1 marks)

Calculate the missing magnetic force in the table.

Question 3 (2 marks)

Identify a mathematical relationship between the force acting on the conductor and the current passing through the conductor, including the uncertainty of the gradient.



CHAPTER

07 Electromagnetic induction

In 1831, Englishman Michael Faraday and American Joseph Henry independently made a discovery that would change the way electricity is produced. These scientists discovered that a changing magnetic flux (that is, a changing magnetic field through a coil or a loop) could create or induce an electric current in a conductor. This discovery of electromagnetic induction made possible the production of vast quantities of electricity in AC generators. To carry electricity from generators to cities, devices called transformers are used within a large-scale electricity supply system. These transformers modify current and voltage for transmission of electricity to reduce power losses along the way.

Today, whether the primary energy source is burning coal, wind, nuclear fission or falling water, the vast bulk of the world's electrical energy production is the result of electromagnetic induction.

Syllabus subject matter

ELECTROMAGNETIC INDUCTION

- Describe the concepts of magnetic flux, magnetic flux density, electromagnetic induction, electromotive force (EMF), Faraday's Law and Lenz's Law. **7.1**, **7.2**, **7.3**
- Solve problems involving the magnetic flux in an electric current-carrying loop using $\phi = BA\cos\theta$. **7.1**
- Describe the process of inducing an EMF across a moving conductor in a magnetic field. **7.2**, **7.3**
- Explain how Lenz's Law is consistent with the principle of conservation of energy. **7.3**
- Explain how transformers work in terms of Faraday's Law and electromagnetic induction. **7.4**
- Solve problems involving electromagnetic induction using $\text{emf} = -\frac{N\Delta(BA_{\perp})}{\Delta t}$, $emf = -N\frac{\Delta\phi}{\Delta t}$, $I_pV_p = I_sV_s$ and $\frac{V_p}{V_s} = \frac{N_p}{N_s}$. **7.2**, **7.4**
- Describe the concept of an electromagnetic wave. **7.5**
- Explain the relationship between oscillating electric charges and electromagnetic waves. **7.5**

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7.1 Magnetic flux

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- describe magnetic flux and magnetic flux density
- calculate the magnetic flux threading a coil of area, A, when the coil is positioned:
  - parallel to
  - at an angle θ to
  - perpendicular to a magnetic field of strength, B.

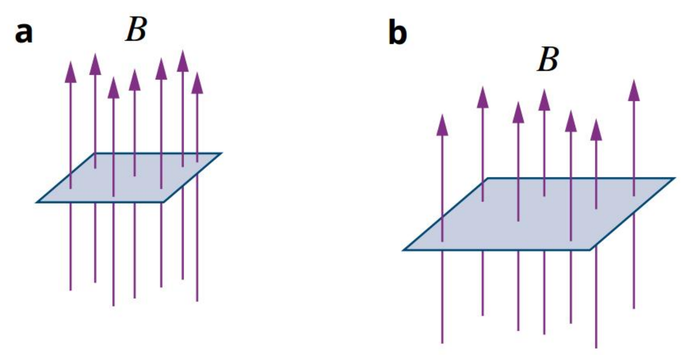


FIGURE 7.1.1 A strong magnetic field acting over a small area (a) will have the same magnetic flux as a weaker magnetic field acting over a larger area (b).

To be able to develop ideas about the change in a **magnetic field**, it is useful to be able to describe the 'amount of magnetic field'. This amount of magnetic field is referred to as the **magnetic flux**, a scalar quantity, denoted by the symbol ϕ. The density of the lines represents the strength of the magnetic field. Magnetic flux can be related to the total number of these lines that pass within a particular area. (This can be referred to as the amount of magnetic flux that threads the coil or area, like thread going through the eye of a needle).

A strong magnetic field acting over a small area can produce the same amount of magnetic flux as a weaker field acting over a larger area (Figure 7.1.1). For this reason, magnetic field strength, B, is also referred to as **magnetic flux density**. B can be thought of as being proportional to the number of magnetic field lines per unit area perpendicular to the magnetic field. The magnetic flux will be at a maximum when the area examined is **perpendicular** to the magnetic field and zero when the area being examined is **parallel** to the magnetic field.

RELATIONSHIP FOR MAGNETIC FLUX

Based on this, magnetic flux is defined as the product of the strength of the magnetic field, B, and the area of the field perpendicular to the field lines. Since it is the area perpendicular to the magnetic field that contributes to magnetic flux, the angle between the magnetic field and the area through which the field passes will affect the amount of magnetic flux. As the angle increases or decreases from 90°, the amount of magnetic flux will decrease until it is zero when the area under consideration is parallel to the magnetic field. Referring to Figure 7.1.2, the relationship between the amount of magnetic flux and the angle θ to the field is $\phi = BA\cos\theta$.

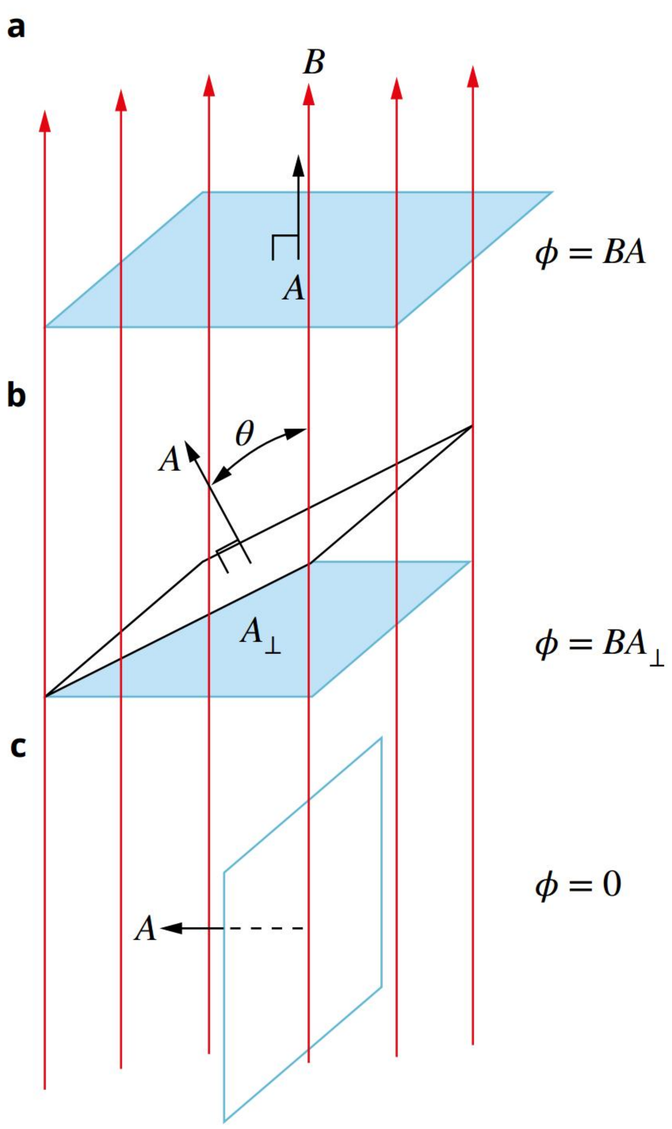


FIGURE 7.1.2 The magnetic flux is the strength of the magnetic field, B, multiplied by the area perpendicular to the magnetic field, given by $A\cos\theta$ and shown as the shaded areas in the above diagrams.

$\phi = BA\cos\theta$

where

ϕ is the magnetic flux. The unit for magnetic flux is the weber, abbreviated to Wb (1 Wb = 1 T m^2)

B is the strength of the magnetic field in tesla (T)

A is the area in square metres (m^2)

θ is the angle between a normal to the area and the direction of the magnetic field.

It is important to note that θ is not the angle between the plane of the area and the magnetic field. Rather, it is the angle between a normal to the area and the direction of the magnetic field; hence the use of $\cos\theta$. When the area is at right angles to the magnetic field, the angle θ between the normal and the field is 0° and $\cos 0° = 1$ (Figure 7.1.2a). When the area is parallel to the magnetic field, the angle θ between the normal and the field is 90° and $\cos 90° = 0$ (Figure 7.1.2c).

For the case where the area is perpendicular to the magnetic field ($\theta = 90°$), the formula for magnetic flux can be rewritten as $\phi = BA_{\perp}$. The subscript $\perp$ is included in the formula to indicate that the area referred to is perpendicular to the magnetic field.

Worked example 7.1.1

MAGNETIC FLUX WITH AREA PERPENDICULAR TO A MAGNETIC FIELD

A student places a horizontal square coil of wire of side length 5.0 cm into a uniform vertical magnetic field of 0.10 T. Calculate how much magnetic flux threads the coil.

Thinking	Working
Calculate the area of the coil perpendicular to the magnetic field.	side length = 5.0 cm = 0.05 m area of the square = $(0.05\,\text{m})^2$ $= 0.0025\,\text{m}^2$
Calculate the magnetic flux. Note that the area is perpendicular to the field.	$\phi = BA\cos\theta = BA_{\perp}$ $= 0.1 \times 0.0025$ $= 0.00025\,\text{Wb}$
State the answer in an appropriate form.	$\phi = 2.5 \times 10^{-4}\,\text{Wb}$ or 0.25 mWb

➤ Try yourself 7.1.1

MAGNETIC FLUX WITH AREA PERPENDICULAR TO A MAGNETIC FIELD

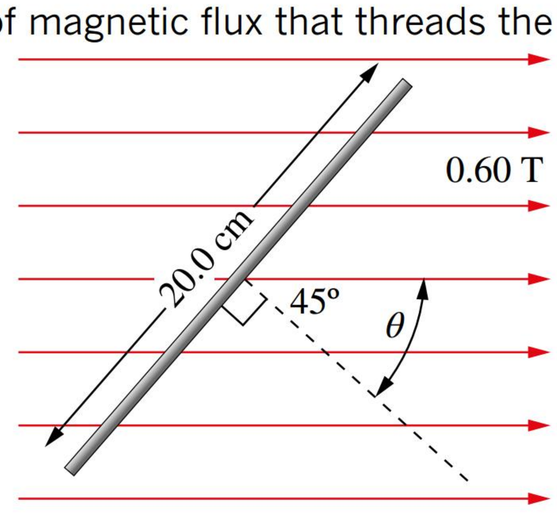
Aksh places a horizontal square coil of wire of side length 4.0 cm into a uniform vertical magnetic field of 0.050 T. Calculate how much magnetic flux threads the coil.

Worked example 7.1.2

MAGNETIC FLUX WITH AREA AT AN ANGLE TO A MAGNETIC FIELD

Isabelle places a horizontal square coil of wire of side length 20.0 cm into a uniform horizontal magnetic field of 0.60 T. The normal to the coil makes an angle of 45° to the magnetic field.

Determine the amount of magnetic flux that threads the coil.



Thinking	Working
Calculate the area of the coil.	side length = 20.0 cm = 0.20 m area of the square = $(0.20\,\text{m})^2$ $= 0.04\,\text{m}^2$
Calculate the component of the magnetic flux density that is acting perpendicular to the coil.	$\phi = BA\cos\theta$ $= 0.6 \times 0.04 \times \cos 45°$ $= 0.01697\,\text{Wb}$
State the answer in an appropriate form.	$\phi = 1.7 \times 10^{-2}\,\text{Wb}$ or 17 mWb

➤ Try yourself 7.1.2

MAGNETIC FLUX WITH AREA AT AN ANGLE TO A MAGNETIC FIELD

Isabelle now replaces the original square coil of wire with one that has a side length of 35.5 cm. She rotates the coil of wire so the normal to the coil makes an angle of 65° to the original horizontal magnetic field. Determine the amount of magnetic flux that threads the coil.

7.1 Review

SUMMARY

- Magnetic flux is defined as the product of the strength of the magnetic field, B, and the area of the field A perpendicular to the field lines.
- Magnetic flux density describes the density of magnetic field lines through a given area and hence is equivalent to the magnetic field strength (T).
- The equation for magnetic flux is $\phi = BA\cos\theta$, where θ is the angle between a normal to the area and the direction of the magnetic field.
- The amount of magnetic flux is at maximum when the area is perpendicular ($\theta = 0°$ to the normal) to the field and zero when the area is parallel ($\theta = 90°$ to the normal) to the field.
- The unit for magnetic flux is the weber, Wb: $1\,\text{Wb} = 1\,\text{T}\,\text{m}^2$.

KEY QUESTIONS

Describe

1 Recall what the density of magnetic field lines shows.

2 Identify if the following are scalar or vector quantities:

a magnetic field

b magnetic flux

c magnetic flux density.

3 For a loop of area A placed inside a magnetic field of strength B, the magnetic flux threading through the loop is defined as $\phi = BA\cos\theta$. Describe where the angle θ is measured to complete the calculation.

4 Compare magnetic flux to magnetic flux density.

Apply

5 If the area is increased, describe what needs to happen to keep the magnetic flux constant?

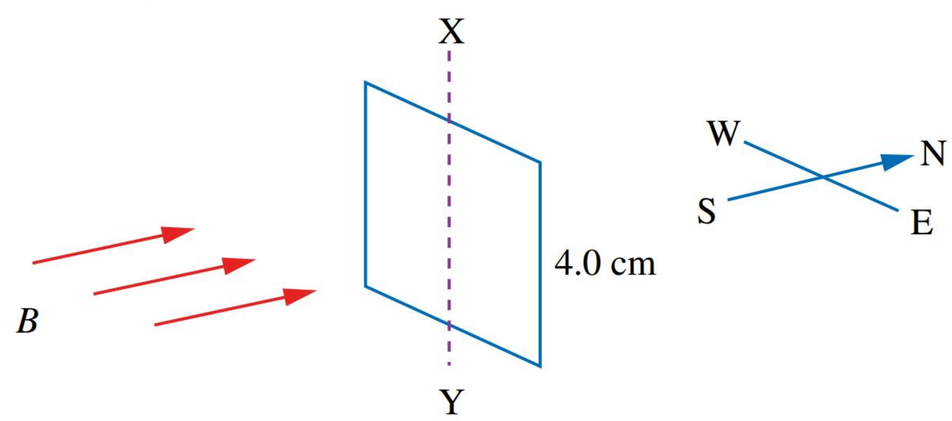
6 Determine how much magnetic flux 'threads' a 4.0 cm square coil of wire parallel to a uniform vertical magnetic field of 0.050 T.

7 A coil with area of $2.0\,\text{cm}^2$ is at an angle of 30° to a magnetic field of strength 1.3 mT. Calculate the magnetic flux.

Analyse

8 A circular loop of wire is placed within a magnetic field of strength 1.0 T and produces a magnetic flux of 6.7×10^{-5} Wb when at an angle of 36°. Calculate the radius of the loop.

9 A square loop of wire of side 4.0 cm is in a region of uniform magnetic field, $B = 2.0 \times 10^{-3}$ T north, as in the diagram below. The loop is free to rotate about a vertical axis XY. When the loop is in its initial position, its plane is perpendicular to the direction of the magnetic field.

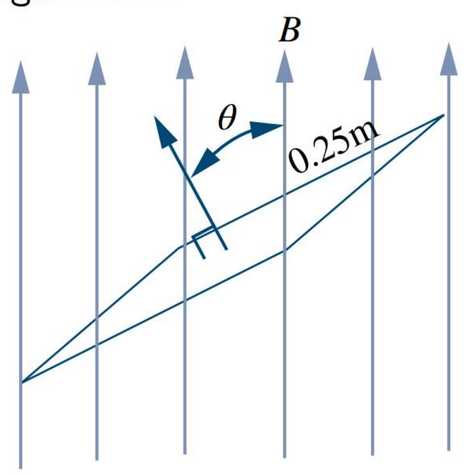


a Calculate the magnetic flux passing through the loop.

b Describe what happens to the amount of magnetic flux passing through the loop as the loop is rotated through one complete revolution.

c The loop now remains stationary, but the source of the magnetic field rotates in a 180° arc around the loop. Determine if flux changes in the same way as it did when the loop was rotated. Explain your response.

10 The amount of flux threading the 0.25 m square loop shown in the diagram below is 4.2×10^{-2} Wb. The loop is placed at an angle θ inside a uniform magnetic field of strength 0.82 T.



$$\phi = BA_{\perp}$$

a Calculate the angle between the normal to the loop and the magnetic field.

b Determine the size of the angle between the loop itself and the magnetic field.

7.2 Faraday's law of electromagnetic induction

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- describe electromagnetic induction
- recognise that an electromotive force (EMF) is induced in a conductor when there is a change in magnetic flux
- explain why there is a separation of charges at opposite ends of a conductor that is moving perpendicular to a magnetic field
- describe Faraday's law of induction
- use Faraday's law to calculate the EMF induced by a changing magnetic flux.

Michael Faraday, an English scientist, conducted a simple experiment in the 1800s to see if it was possible to produce an electric current from a magnetic field. Figure 7.2.1 shows a simplified version of this experiment. Imagine that a strong electric current is fed into the coil on the left-hand side of Figure 7.2.1. Faraday knew that this would create a magnetic field around this coil. He expected that this magnetic field would produce a current in the coil on the right side of the iron ring. But the galvanometer (a simple ammeter) only flickered when the current in the first loop was turned on or off. This observation confirmed that it is possible for an electric current to be created due to a magnetic field. However, a steady magnetic field alone will not produce an electric current. The needle on the galvanometer scale only moved when the magnetic field was changing. When the current in the first loop stayed on, the reading on the galvanometer dropped to zero.

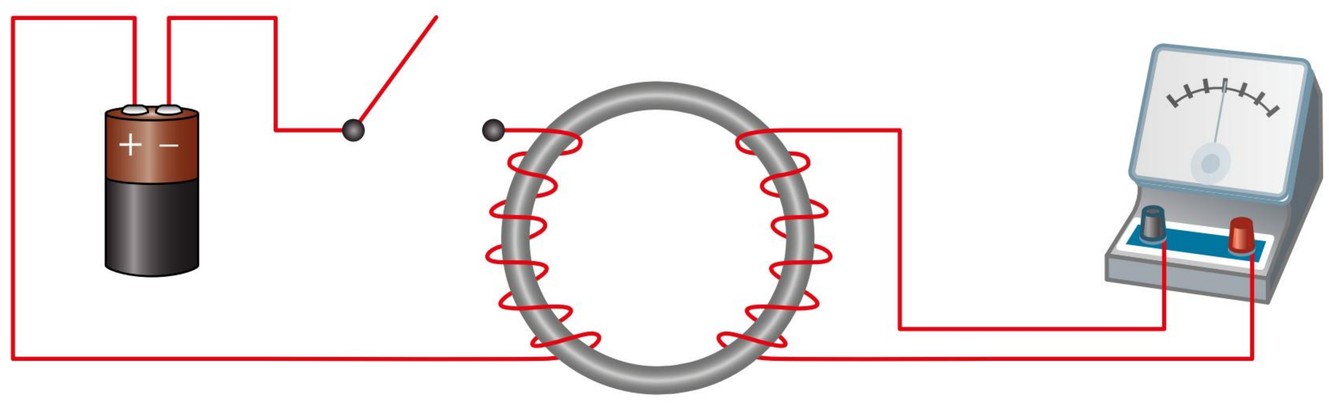


FIGURE 7.2.1 A modern set up of Michael Faraday's experiment to produce an electric current from a magnetic field, an electric current is fed into a coil wrapped around an iron ring and the current is measured by a galvanometer.

CREATING AN ELECTRIC CURRENT

The creation of an electric current in a conductor due to a change in the magnetic field acting on that conductor is called **electromagnetic induction**. In fact, any change in magnetic flux through a conductor creates or induces an electric current. This change in flux may result from a change in the area, a change in magnetic field strength or a change in the angle of flux through the conductor. The discovery of electromagnetic induction has changed the world, enabling the generation of electricity.

INDUCED EMF

An electric current is created in a conductor whenever there is a change in magnetic flux. This current is produced by an induced EMF. Although the term 'EMF' is derived from the name **electromotive force**, it is a voltage, or potential difference, rather than a force. Figure 7.2.2 indicates the induction of an EMF, and therefore current, caused by the perpendicular movement of a conducting wire relative to a magnetic field.

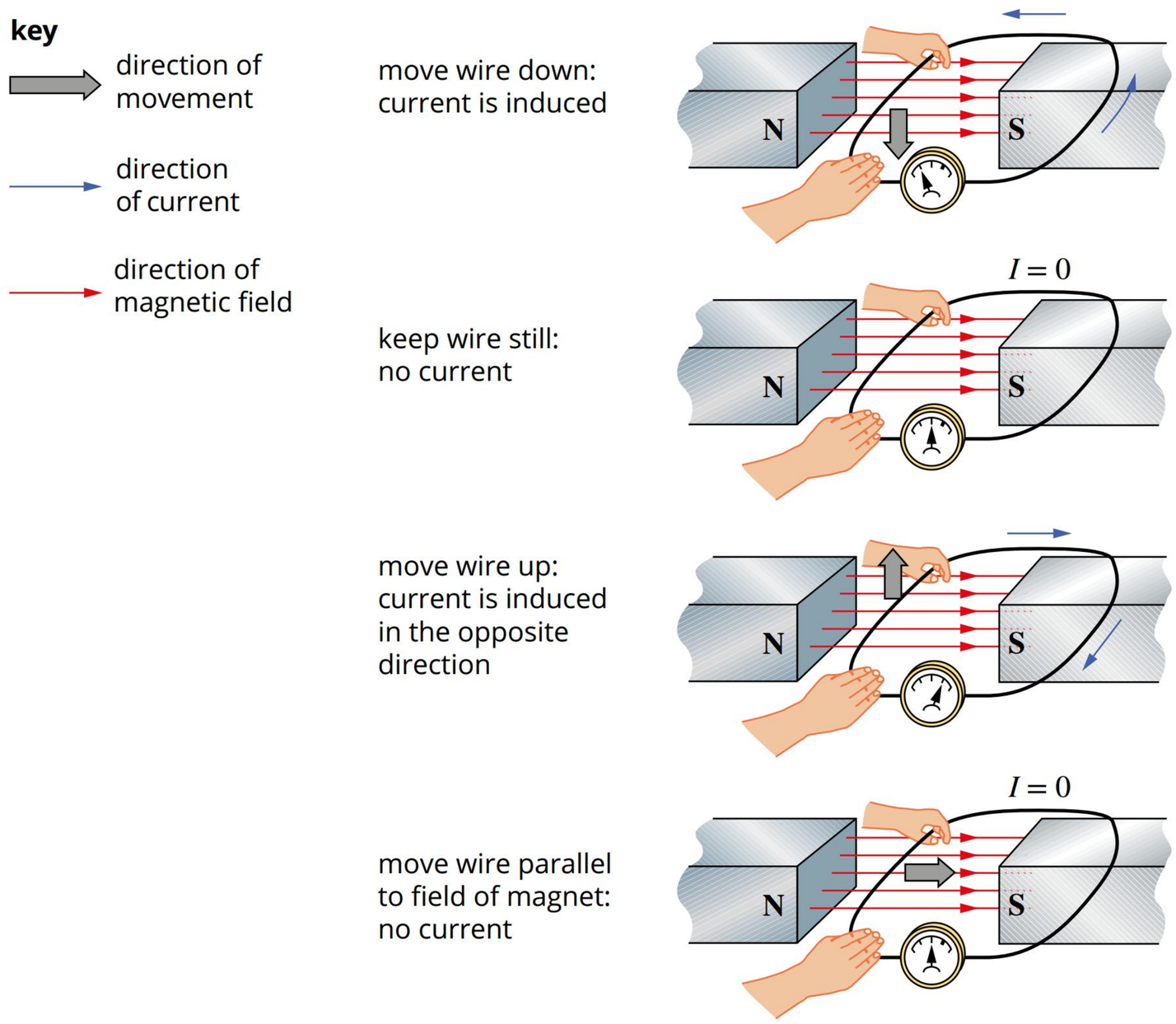


FIGURE 7.2.2 An EMF is induced in a wire when it moves perpendicular to a magnetic field.

Electromotive force can be abbreviated to EMF or emf.

Faraday largely based his investigations on **induced currents** in coils, but another way of inducing an EMF is by moving a straight conductor in a magnetic field. It is not hard to understand why this is the case, when you know that charges moving in a magnetic field will experience a force.

In Chapter 6, it was established that when a charge, q, moves at a speed, v, perpendicular to a magnetic field, B, the charge experiences a force, F, and $F = qvB \sin\theta$.

Considering the direction of movement shown in Figure 7.2.3 and applying the right-hand slap rule with your thumb pointing to the left in the direction of the movement of a positive charge, and the magnetic field acting downwards, these positive charges experience a force along the conductor and out of the page. The force on the negative charges within the conductor would be along the conductor but into the page.

As the charges in Figure 7.2.3 move apart due to the force they are experiencing from the magnetic field, one end of the conductor will become more positive and the other more negative, and a potential difference, V, or EMF will be induced between the ends of the conductor.

Consider now an electron moving along the conductor. The force from the magnetic field will do work on the electron as it moves along a length, L. Recall from *Pearson Physics Queensland Units 1 & 2* that the work done is equal to the change in energy. In this case, the work done is equivalent to the change in electrical potential energy. To calculate the work done:

$\Delta U = W = \text{force} \times \text{displacement} = qvB \sin\theta \times L$

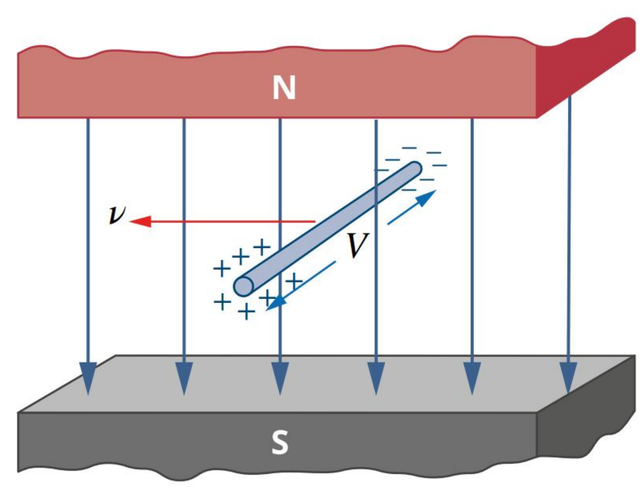


FIGURE 7.2.3 A potential difference, ΔV, will be produced across a straight wire moving to the left in a downwards-pointing magnetic field.

The EMF is equal to the work done per unit charge, so:

$$emf = \frac{\Delta U}{q} = \frac{W}{q} = \frac{qvB\sin\theta L}{q}$$

and thus:

$$emf = vBL\sin\theta$$

where

emf is the induced EMF (V)

L is the length of the conductor (m)

v is the speed of the conductor perpendicular to the magnetic field ($m\,s^{-1}$)

B is the strength of the magnetic field (T)

θ is the angle between the charge and the magnetic field (°).

The size of the induced EMF increases as the speed of the conductor increases. Note that if the conductor were to move parallel to the magnetic field, then there would be no EMF induced.

Factors affecting induced EMF

There are various factors which affect the size of the EMF induced in a coil. First, an EMF will be induced by a change in the magnetic field. A simple example of this is to witness the EMF induced when a magnet is brought towards or moved away from a wire coil. The greater the change in the magnetic field strength, the greater the EMF.

An EMF can also be induced by changing the area perpendicular to the magnetic field through which the magnetic field lines pass, A, while keeping B constant. Alternatively, an EMF is induced when the angle through which the magnetic field lines pass through a perpendicular area is changed. An example of this is to witness the EMF induced when a wire coil is rotated in the presence of a fixed magnetic field. This discovery indicates that the requirement for an induced EMF is to have a changing magnetic flux, ϕ.

Finally, the faster the change in magnetic flux, the greater the induced EMF.

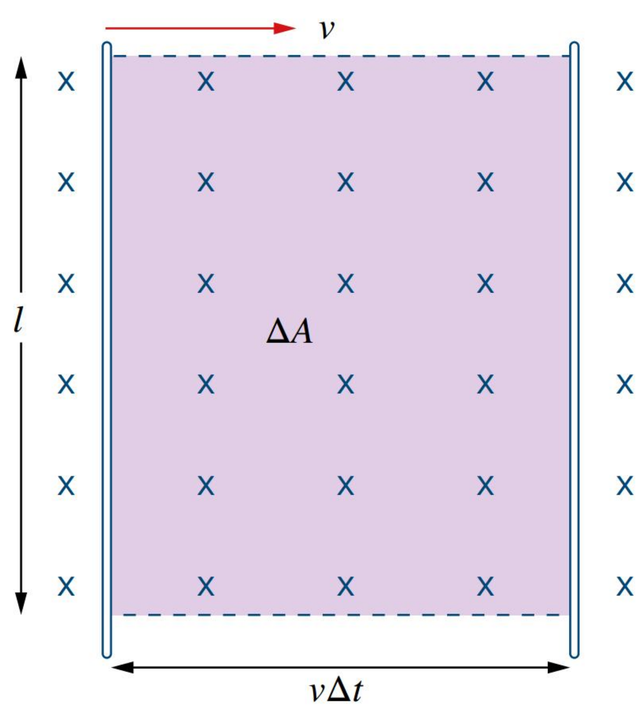


FIGURE 7.2.4 The area, ΔA (shaded), swept out by the wire in the field, B in time, Δt is equal to $Lv\Delta t$.

FARADAY'S LAW OF INDUCTION

Consider a wire of length L moving through a perpendicular magnetic field as shown in Figure 7.2.4. As the wire moves with speed v, it sweeps across lines of magnetic flux. In time Δt the wire moves a distance of $v\Delta t$ and sweeps through an area of $\Delta A = Lv\Delta t$. The amount of flux that is swept through is then:

$$\Delta\phi = B\Delta A = B \times Lv\Delta t$$

This can be written as:

$$BLv = \frac{\Delta\phi}{\Delta t}$$

Remember that the emf = LvB, so emf = $\frac{\Delta\phi}{\Delta t}$. Note that this is shown for the case where $\theta = 90°$, but is also equivalent for various angles.

The magnitude of the EMF generated in the wire is equal to the rate at which the wire is sweeping through the flux. Although this derivation was for a straight wire moving across a magnetic field, it is also true whenever a change in flux gives rise to an EMF.

This is now known as **Faraday's law of induction** and is one of the basic laws of electromagnetism.

If the flux through N turns (or loops) of a coil changes from ϕ_1 to ϕ_2 during a time Δt, then the average induced EMF during this time will be:

$$emf = -N\frac{(\phi_2 - \phi_1)}{\Delta t}$$

and if the change in magnetic flux $\phi_2 - \phi_1 = \Delta\phi$, then:

$$emf = -N\frac{\Delta\phi}{\Delta t} = -\frac{N\Delta(BA_\perp)}{\Delta t}$$

Where emf is the electromotive force (V)

N is the number of turns

$\Delta\phi$ is the change in magnetic flux (Wb)

Δt is the change in time (s)

B is the magnetic field strength (T)

$A_\perp$ is the area perpendicular to the magnetic field (m^2).

The negative sign is placed there as a reminder of the direction of the induced EMF. This is discussed further in Module 7.3. Sometimes, you will only be concerned with the magnitude of the EMF, which means you don't consider the negative sign or any negative quantities in a calculation.

If the ends of the coil are connected to an external circuit, then a current, I, will flow. The magnitude of the current is found using Ohm's law, introduced in *Pearson Physics Queensland Units 1 & 2*:

$$V = IR$$

A coil not connected to a circuit will act like a battery not connected to a circuit. There will still be an induced EMF but no current will flow.

When using Faraday's Law, N is the number of loops of a coil that the magnet flux is cutting.

Don't confuse this with the magnetic field of a solenoid where n is the number of loops per metre.

How to change the magnetic flux

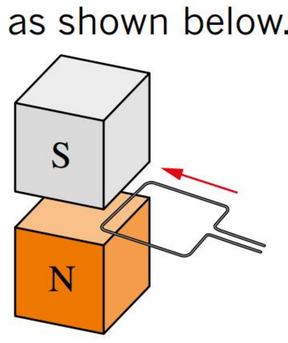
It is important to note that any change in magnetic flux will, by Faraday's law, produce an EMF. The magnetic flux could change in several ways, or in a combination of several factors, such as a change in the:

- area of coil
- magnetic field strength
- angle of flux threading a loop.

Worked example 7.2.1

INDUCED EMF IN A COIL

A student winds a coil of area 40.0 cm^2 and places it horizontally in a vertical uniform magnetic field of 0.10 T, as shown below.



a Calculate the magnetic flux perpendicular to the coil.

Thinking	Working
Identify the quantities to calculate the magnetic flux through the coil and convert to SI units where required.	$B = 0.10\,T$ $A = 40\,cm^2 = 40 \times 10^{-4}\,m^2$
Calculate the magnetic flux and give your answer with appropriate units. Note that the area is perpendicular to the field.	$\phi = BA\cos\theta = BA_\perp$ $= 0.10 \times 40 \times 10^{-4}$ $= 4.0 \times 10^{-4}\,Wb$

b Calculate the magnitude of the average induced EMF in the coil when the coil is removed from the magnetic field in a time of 0.5 s.	
Identify the quantities for determining the induced EMF. Ignore the negative sign.	$\Delta\phi = \Delta\phi_2 - \Delta\phi_1$ $= 0 - 4.0 \times 10^{-4}$ $= 4.0 \times 10^{-4}\,\text{Wb}$ $\Delta t = 0.5\,\text{s}$
Calculate the magnitude of the average induced EMF, ignoring the negative sign that indicates the direction.	$emf = -N\dfrac{\Delta\phi}{\Delta t}$ $= \dfrac{4.0 \times 10^{-4}}{0.5}$ $= 0.0008\,\text{V}$ or $8.0 \times 10^{-4}\,\text{V}$

➤ Try yourself 7.2.1

INDUCED EMF IN A COIL

Laura winds a coil of area $50.0\,\text{cm}^2$ with exactly 10 turns. She places it horizontally in a vertical uniform magnetic field of 0.10 T.

a Calculate the magnetic flux perpendicular to the coil.

b Calculate the magnitude of the average induced EMF in the coil when the coil is removed from the magnetic field in a time of 1.0 s.

Worked example 7.2.2

NUMBER OF TURNS IN A COIL

A coil of cross-sectional area $1.0 \times 10^{-3}\,\text{m}^2$ is placed next to an electromagnet that is initially turned off. When it is switched on, the magnetic field strength increases from zero to 0.20 T in 0.50 s. The magnitude of the average induced EMF is measured as 0.10 V. Determine the number of turns that must be on the coil.

Thinking	Working
Identify the quantities needed to calculate the magnetic flux through the coil when in the presence of the magnetic field and convert to SI units where required.	$B = 0.20\,\text{T}$ $A = 1.0 \times 10^{-3}\,\text{m}^2$
Calculate the magnetic flux when in the presence of the magnetic field.	$\phi = BA\cos\theta = BA_{\perp}$ $= 0.20 \times 1.0 \times 10^{-3}$ $= 2.0 \times 10^{-4}\,\text{Wb}$
List the known quantities and those required to complete Faraday's law.	$N = ?$ $\Delta\phi = \phi_1 - \phi_2$ $= 2.0 \times 10^{-4} - 0$ $= 2.0 \times 10^{-4}\,\text{Wb}$ $\Delta t = 0.50\,\text{s}$ $emf = 0.10\,\text{V}$
Rearrange Faraday's law and solve for the number of turns on the coil, n. Ignore the negative sign.	$emf = -N\dfrac{\Delta\phi}{\Delta t}$ $N = -\dfrac{emf\,\Delta t}{\Delta\phi}$ $\dfrac{0.10 \times 0.50}{2.0 \times 10^{-4}}$ $= 250$ turns

➤ Try yourself 7.2.2

NUMBER OF TURNS IN A COIL

A coil of cross-sectional area $2.0 \times 10^{-3}\,m^2$ is placed next to an electromagnet that is initially turned off. When it is switched on, the magnetic field strength increases from zero to 0.20 T in 1.00 s. The magnitude of the average induced EMF is measured as 0.40 V. Determine the number of turns that must be on the coil.

7.2 Review

SUMMARY

- An induced EMF is produced by a changing magnetic flux in a process called electromagnetic induction.
- The induced EMF in a straight conductor moving in a magnetic field, B, is given by $emf = LvB \sin\theta$.
- The direction of the induced EMF can be found using the right-hand slap rule.
- The EMF induced in a conducting loop in which there is a changing magnetic flux is proportional to the negative rate of change of flux.
- $emf = -N\dfrac{\Delta\phi}{\Delta t}$, which is Faraday's law of induction.

  This can also be written as $\text{emf} = -\dfrac{N\Delta(BA_{\perp})}{\Delta t}$.
- N is the number of loops or coils of wire that the magnetic flux is cutting.
- According to Faraday's law, an EMF can be induced by a change in:
  - the area of a coil
  - the number of coils inside a magnetic field
  - magnetic field strength
  - angle of flux threading a loop
  - timeframe in which flux is being altered.
- The negative sign in Faraday's law indicates direction. For questions involving only magnitudes, you should not use the negative sign or any negative quantities.

KEY QUESTIONS

Describe

1 Faraday's law states that a changing magnetic flux will produce an EMF. Recall the units of EMF.

2 State three ways in which the magnetic flux through a loop in a magnetic field may change.

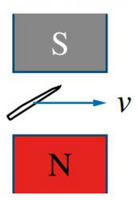
3 Identify the relationship between EMF and potential difference.

4 Describe the change in an induced EMF if the area of a coil is increased.

5 Describe the change in an induced EMF if the time in which the flux is altered is decreased.

Apply

6 A conductor is moving in a magnetic field as shown.

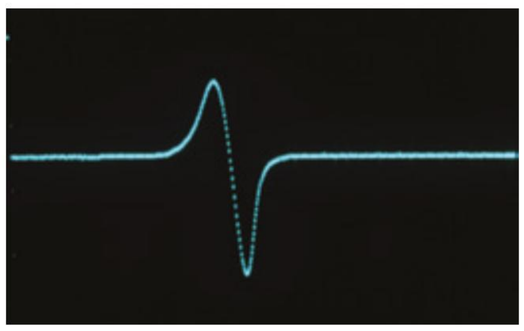


a Determine how a potential difference is induced across the length of the conductor.

b If this conductor was connected to a circuit, identify which direction would the induced current flow?

7 A coil of cross-sectional area $1.5 \times 10^{-3}\,m^2$ is placed next to an electromagnet that is initially turned off. When it is switched on, the magnetic field strength increases from zero to 0.32 T in 0.58 s. The magnitude of the average induced EMF is measured as 0.60 V. Calculate the number of turns that must be on the coil.

8 When a magnet is dropped through a coil, a voltage sensor will detect an induced voltage in the coil as shown below.



a Explain, in terms of Faraday's law and induced EMF, why the pulse shown changes from a positive to a negative.

b Explain why the pulse magnitude is larger on the negative side than the positive side.

7.2 Review *continued*

Analyse

9 Consider the conductor shown in Figure 7.2.4, which is moving inside a vertical magnetic field. In the instant shown in the diagram, the conductor is moving to the left and positive charges are pushed along the conductor out of the page. Predict what will happen to the charge separation if the conductor:

a moves to the right

b continuously oscillates horizontally back and forth inside the magnetic field.

10 A student conducts an experiment to measure the induced current in a coil by varying the number of turns. They collect the following data by moving a bar magnet in and out of the coil at a constant speed.

Number of turns	Average current (mA)
50	2.1
100	4.3
150	6.2
200	8.5
250	10.7

a Create a graph of the number of turns against the measured current. Describe the shape of the graph.

b Justify how this validates Faraday's law and identify the proportional relationship between the number of turns and the induced EMF.

c Predict what you think would happen to the results if the speed with which the bar magnet is moved into the coil is increased.

11 A circular coil of wire with 50 turns is placed in a magnetic field that experiences a change of 1.6 T in 30 s. Calculate the radius of the coil if the induced EMF is 5.4 V.

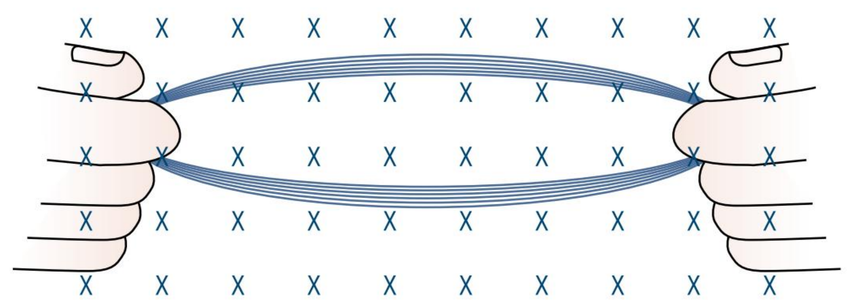
The following information relates to questions **12–13**. A coil of exactly 500 turns, each of area 10.0 cm^2, is wound around a square frame. The plane of the coil is initially parallel to a uniform magnetic field of 80.0 mT. The coil is then rotated through an angle of 90.0° so that the coil is now perpendicular to the field. The rotation is completed in 20.0 ms.

12 Calculate the magnitude of the average EMF induced in each turn of the coil during this time.

13 Calculate the total average EMF induced in the coil during the time the coil rotated.

14 Gayathri stretches a flexible wire coil of exactly 30 turns and places it in a uniform magnetic field of strength 5.0 mT that is directed into the page, as shown in the diagram below. While it is in the field, she allows the coil to regain its original shape. In doing so, the area of the coil changes at a constant rate from 250 cm^2 to 50.0 cm^2 in 0.50 s.

Determine the average EMF induced in the coil during this time.



7.3 Lenz's law and its applications

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- describe how to find the direction of the induced current in a conductor according to Lenz's law
- explain that Lenz's law is predicted by the law of conservation of energy
- outline how a magnetic flux varies in an AC generator and how an EMF is induced.

Lenz's law, which is the focus of this section, is a common way of understanding how electromagnetic induction obeys the principle of conservation of energy and explains the direction of the induced EMF. It is named after Heinrich Lenz, whose research put a definite direction to the current (Figure 7.3.1) created by the induced EMF resulting from a changing magnetic flux.

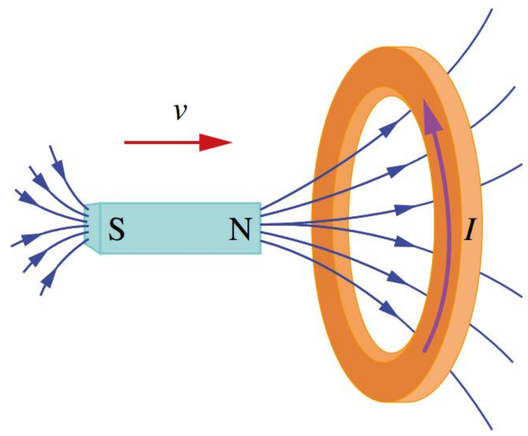


FIGURE 7.3.1 The purple arrow indicates the direction of the induced current, *I*, which can be found using Lenz's law.

THE DIRECTION OF AN INDUCED EMF

Figure 7.3.2 applies Lenz's law to the relative motion between a magnet and a single coil of wire. Moving the magnet towards or away from the coil will induce an EMF in the coil, as there is a change in flux. The induced EMF will produce a current in the coil. This induced current will then produce its own magnetic field. It is worth noting that Lenz's law is a necessary consequence of the law of conservation of energy. If Lenz's law were not true then the new magnetic field created by a changing flux would increase the original changing flux, which in turn would create more current, and so on. This violates the law of conservation of energy.

> Lenz's law states that the direction of an induced current is such that it will always oppose the change in flux that created it.

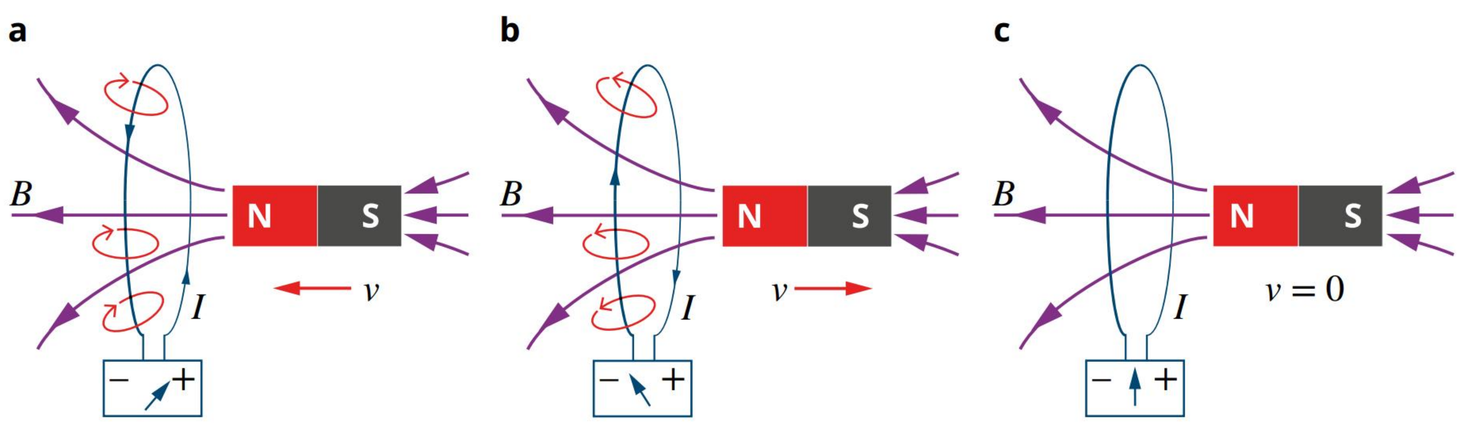


FIGURE 7.3.2 (a) The north end of a magnet is brought towards a coil from right to left, inducing a current that flows anticlockwise. (b) Pulling the north end of the magnet away from the coil from left to right induces a current in a clockwise direction. (c) Holding the magnet still creates no change in flux and hence no induced current.

Applying Lenz's law, the magnetic field created by the induced current will oppose the change in flux caused by the movement of the magnet. When the north end of a magnet is brought towards the loop from the right (Figure 7.3.2a), there is an increase in the magnetic flux from right to left through the loop. The induced EMF produces a current that flows anticlockwise around the loop when viewed from the right. The magnetic field created by this current, shown by the little circles around the wire, is directed from left to right through the loop. It opposes the magnetic field of the approaching magnet.

If the magnet is moved away from the loop (Figure 7.3.2b), the magnetic flux from right to left through the loop decreases. The induced EMF produces a clockwise current when viewed from the right. This creates a magnetic field that is directed from right to left through the loop. This field is in the same direction as the original magnetic field of the retreating magnet. However, note that it is opposing the change in the magnet's flux through the loop by attempting to replace the declining flux.

When the magnet is held stationary (Figure 7.3.2c) there is no change in flux to oppose and so no current is induced.

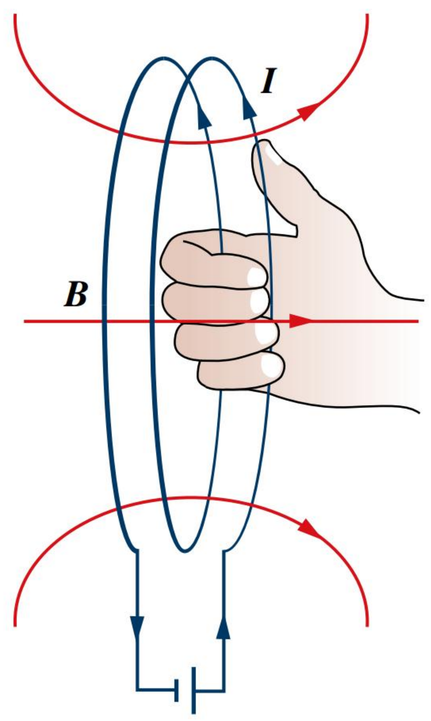


FIGURE 7.3.3 The right-hand grip rule can be used to determine the direction of a magnetic field from a current or vice versa. Your thumb points in the direction of the conventional current in the wire and your curled fingers indicate the direction of the magnetic field through the coil.

The right-hand grip rule and induced current direction

The right-hand grip rule (see Chapter 6) can be used to find the direction of the induced current. Keep in mind that the current must create a magnetic field that opposes the change in flux due to the relative motion of the magnet and conductor. Point your fingers through the loop in the direction of the field that is opposing the change, and your thumb will then indicate the direction of the conventional current (Figure 7.3.3).

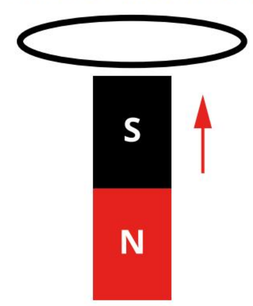
There are three distinct steps to determine the induced current direction according to Lenz's law:

1 What is the change in flux that is happening?
2 What will oppose this change in flux?
3 What must be the direction of the current that would match this opposition?

Worked example 7.3.1

INDUCED CURRENT IN A COIL FROM A PERMANENT MAGNET

The south pole of a magnet is brought upwards towards a horizontal coil held above it. Determine the direction of the induced current flow in the coil.

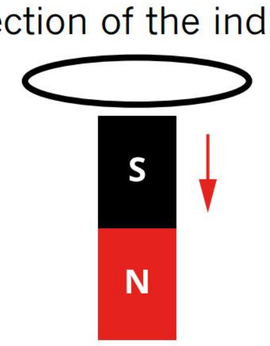


Thinking	Working
Consider the direction of the change in magnetic flux.	The magnetic field direction from the magnet will be downwards towards the south pole. The downwards flux from the magnet will increase as the magnet is brought closer to the coil. So, the change in flux is increasing downwards.
What will oppose the change in flux?	The induced magnetic field that opposes the change would act upwards.
Determine the direction of the induced current required to oppose the change.	To oppose the change, the current direction would be anticlockwise when viewed from above (using the right-hand grip rule).

➤ Try yourself 7.3.1

INDUCED CURRENT IN A COIL FROM A PERMANENT MAGNET

The north pole of a magnet is moved downwards away from a horizontal coil held above it. Determine the direction of the induced current flow in the coil.



Worked example 7.3.2

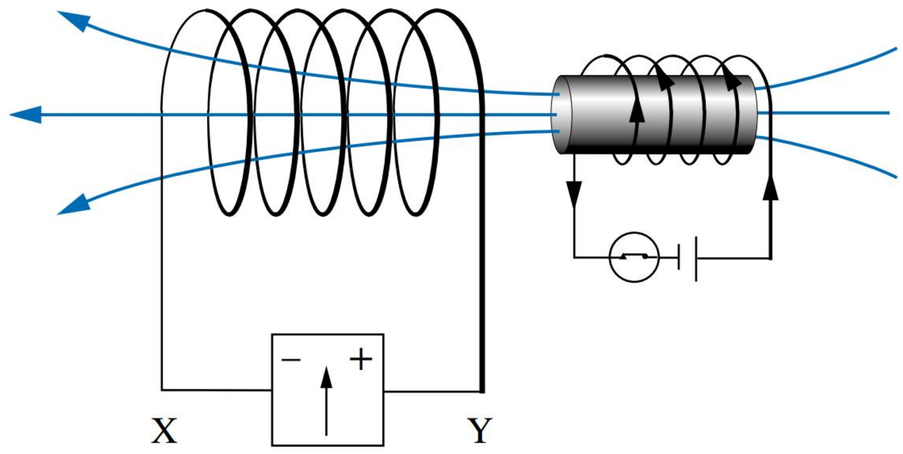
INDUCED CURRENT IN A COIL FROM AN ELECTROMAGNET

Instead of using a permanent magnet to change the flux in the loop as in Worked example 7.3.1, an electromagnet (on the right in the diagram below) could be used. Determine the direction of the current induced in the solenoid when the electromagnet is:

i switched on

ii left on

iii switched off.



Thinking	Working
Consider the direction of the change in magnetic flux for each case.	**i** Initially there is no magnetic flux through the solenoid. When the electromagnet is switched on, the electromagnet creates a magnetic field directed to the left. So, the change in flux through the solenoid is increasing to the left. **ii** While the current in the electromagnet is steady, the magnetic flux through the solenoid is constant. **iii** In this case, initially there is a magnetic flux through the solenoid from the electromagnet directed to the left. When the electromagnet is switched off, there is no longer a magnetic flux through the solenoid. So, the change in flux through the solenoid is decreasing to the left.
Identify what will oppose the change in flux for each case.	**i** The magnetic field that opposes the change in flux through the solenoid is directed to the right. **ii** There is no change in flux and so there will be no opposition needed and no magnetic field created by the solenoid. **iii** The magnetic field that opposes the change in flux through the solenoid is directed to the left.

Determine the direction of the induced current required to oppose the change for each case.	**i** To oppose the change, the current will flow through the solenoid in the direction from X to Y (or through the meter from Y to X), using the right-hand grip rule. **ii** There will be no induced EMF or current in the solenoid. **iii** To oppose the change, the current will flow through the solenoid in the direction from Y to X (or through the meter from X to Y), using the right-hand grip rule.

➤ Try yourself 7.3.2

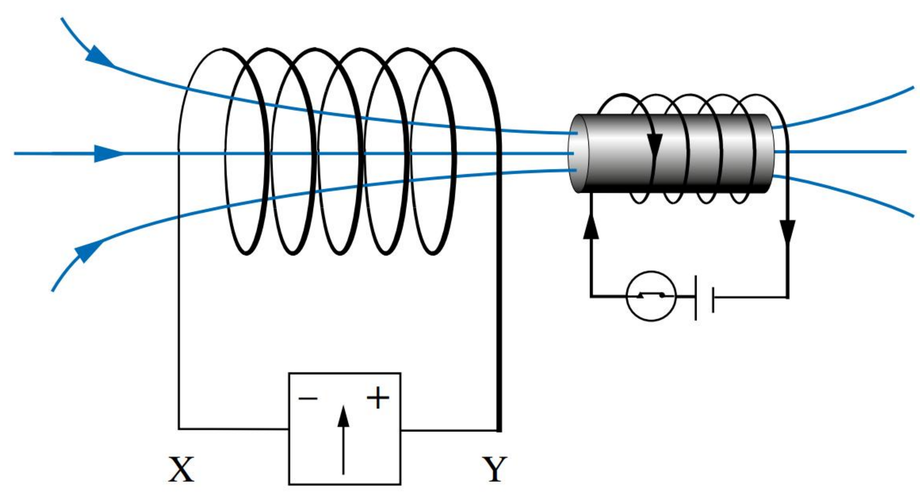
INDUCED CURRENT IN A COIL FROM AN ELECTROMAGNET

Refer to the diagram below. Determine the direction of the current induced in the solenoid when the electromagnet is:

i switched on

ii left on

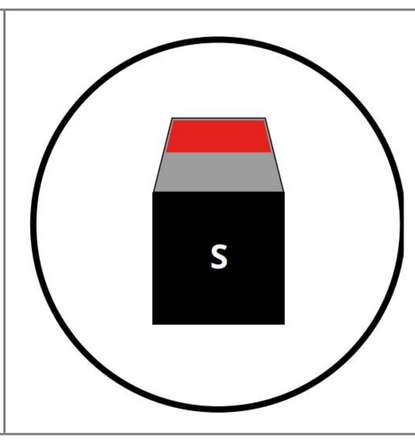
iii switched off.



Worked example 7.3.3

FURTHER PRACTICE WITH LENZ'S LAW

The north pole of a magnet is moving towards a coil, into the page. The south pole is shown at the closer end of the magnet in the diagram. Determine the direction of the induced current flow in the coil while the magnet is moving towards the coil.

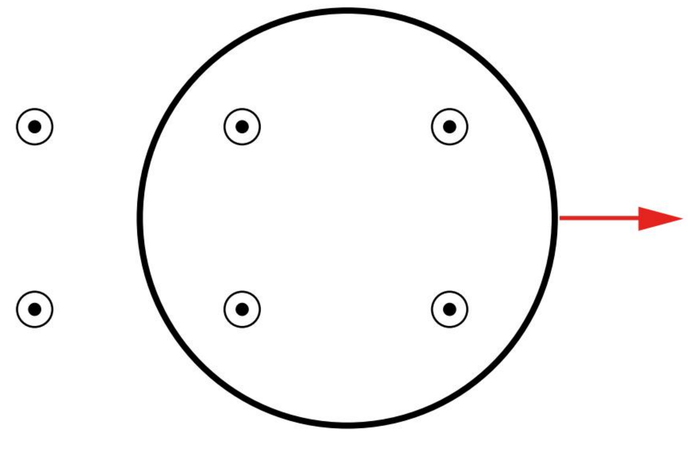


Thinking	Working
Consider the direction of the change in magnetic flux.	The magnetic field direction from the magnet will be away from the north pole, into the page. The flux from the magnet will increase as the magnet is brought closer to the coil. So, the change in flux is increasing into the page.
Identify what will oppose the change in flux.	The magnetic field that opposes the change would act out of the page.
Determine the direction of the induced current required to oppose the change.	To oppose the change, the current direction would be anticlockwise when viewed from the perspective in the diagram (using the right-hand grip rule).

➤ Try yourself 7.3.3

FURTHER PRACTICE WITH LENZ'S LAW

A coil is moved to the right and out of a magnetic field that is directed out of the page. Determine the direction of the induced current flow in the coil while the magnet is moving.



DIFFERENT WAYS TO INDUCE CURRENT

It's important to note that an induced EMF is created while there is a change in flux, no matter how that change is created. As magnetic flux $\phi = BA\cos\theta$, a change can be created by any method that causes a relative change in the strength of the magnetic field, B, and/or the area of the coil perpendicular to the magnetic field. So, an induced EMF can be created in three ways:

- by changing the strength of the magnetic field
- by changing the area of the coil within the magnetic field
- by changing the orientation of the coil with respect to the direction of the magnetic field.

Figure 7.3.4 illustrates an example of the direction of an induced current that results during a decrease in the area of a coil.

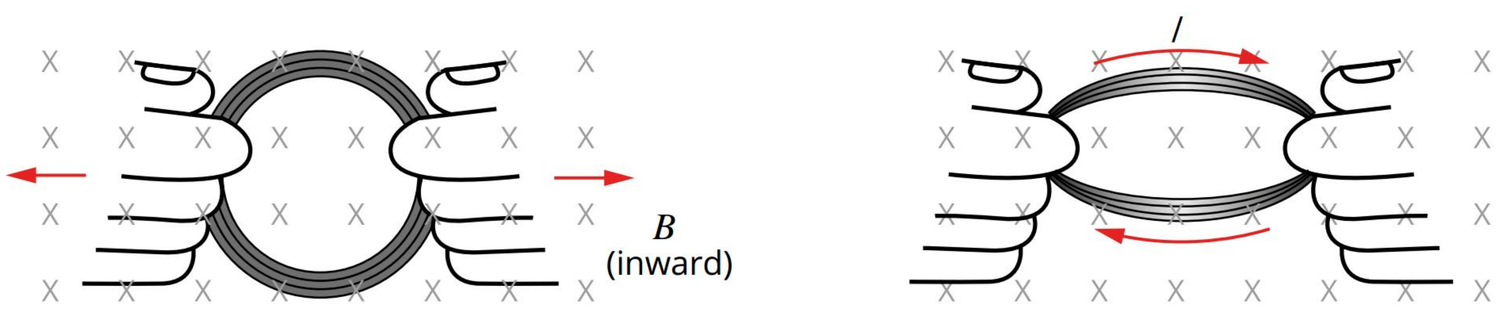


FIGURE 7.3.4 A current is induced by changing the area of a coil. The amount of flux (the number of field lines) through the coil is reduced and an EMF is therefore induced during the time that the change is taking place. The current flows in a direction that creates a field to oppose the reduction in flux into the page.

As the area of the coil decreases due to its changing shape, the flux through the coil (which is directed into the page) also decreases. Applying Lenz's law, the direction of the induced current would oppose this change and will be such that it acts to increase the magnetic flux through the coil into the page. Using the right-hand grip rule, a current would therefore flow in a clockwise direction while the area is changing.

In Figure 7.3.5, the coil is being rotated within the magnetic field. The effect is the same as reducing the area. The amount of flux flowing through the coil is reduced as the coil changes from being perpendicular to the field to being parallel to the field. An induced EMF would be created while the coil is being rotated. This becomes particularly important in determining the current direction in a generator.

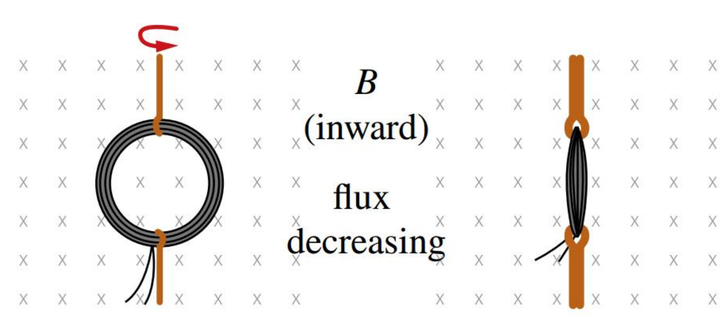
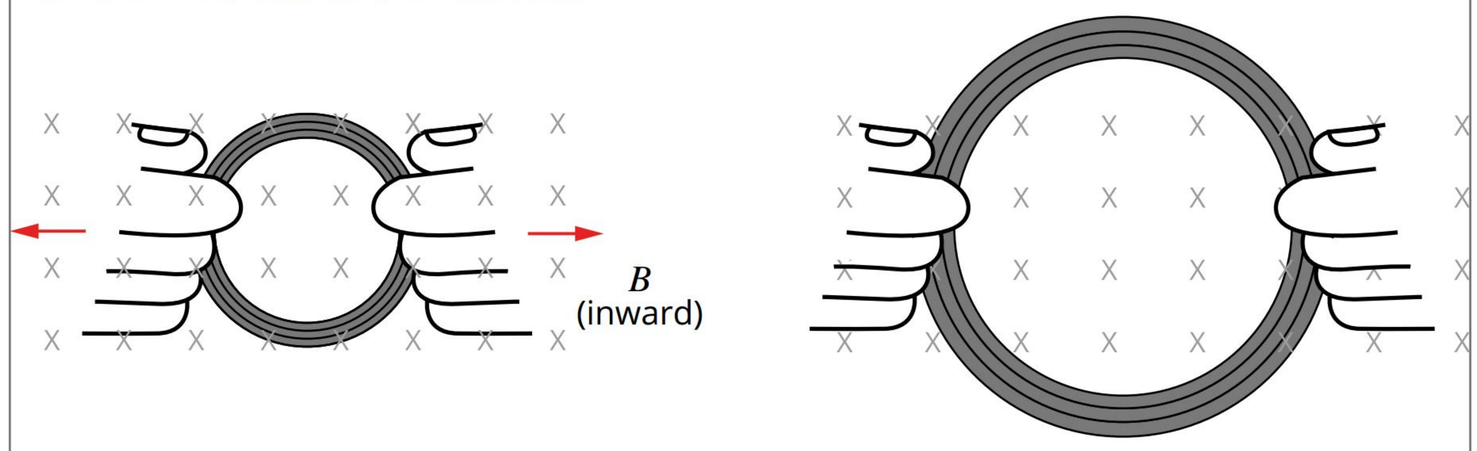


FIGURE 7.3.5 Rotating, or changing the orientation of a coil within a magnetic field reduces the amount of flux through the coil and so induces an EMF in the coil while it is being rotated.

Worked example 7.3.4

INDUCING AN EMF BY CHANGING THE AREA OF A COIL

A coil lies within a magnetic field that points into the page, as shown in the diagram. Initially the coil has a circular shape of radius 2.0 cm. Over a short time, the coil is stretched uniformly to double in radius. Determine the direction of the induced current flow in the coil.



Thinking	Working
Consider the direction of the change in magnetic flux.	The flux threading through the coil increases into the page as the area of the coil increases.
Identify what will oppose the change in flux.	The magnetic field that opposes the change would act out of the page.
Determine the direction of the induced current required to oppose the change.	To oppose the change, the current direction would be anticlockwise when viewed from the perspective in the diagram (using the right-hand grip rule).

➤ Try yourself 7.3.4

INDUCING AN EMF BY CHANGING THE AREA OF A COIL

A flexible square loop of wire lies within a magnetic field that points out of the page. Initially the coil has been stretched so that its sides measure 5 cm. Over a short time, the coil is released and shrinks to its original size of 1 cm^2. Determine the direction of the induced current flow in the coil as it shrinks back to its original size.

APPLICATIONS OF LENZ'S LAW

If a conducting material such as a metal plate encounters a changing magnetic field, then a circular current is induced within the conductor. These induced currents are called eddy currents.

Applying Lenz's law, an eddy current will be in a direction that creates a magnetic field that opposes the change in magnetic flux that created it. Thus, eddy currents can be used to apply a force that opposes the source of the motion of an external magnetic field. For example, if a metal plate is dragged out of a magnetic field, the magnetic flux directed into the plate decreases (Figure 7.3.6). An eddy current is induced inside the plate that opposes this change in flux. The eddy current moves in a clockwise direction and produces more flux through the plate. However, this eddy current within a magnetic field also experiences a magnetic force F, according to $F = BIL$. By the right-hand rule, this magnetic force acts to the left, opposing the motion of the plate and slowing it down.

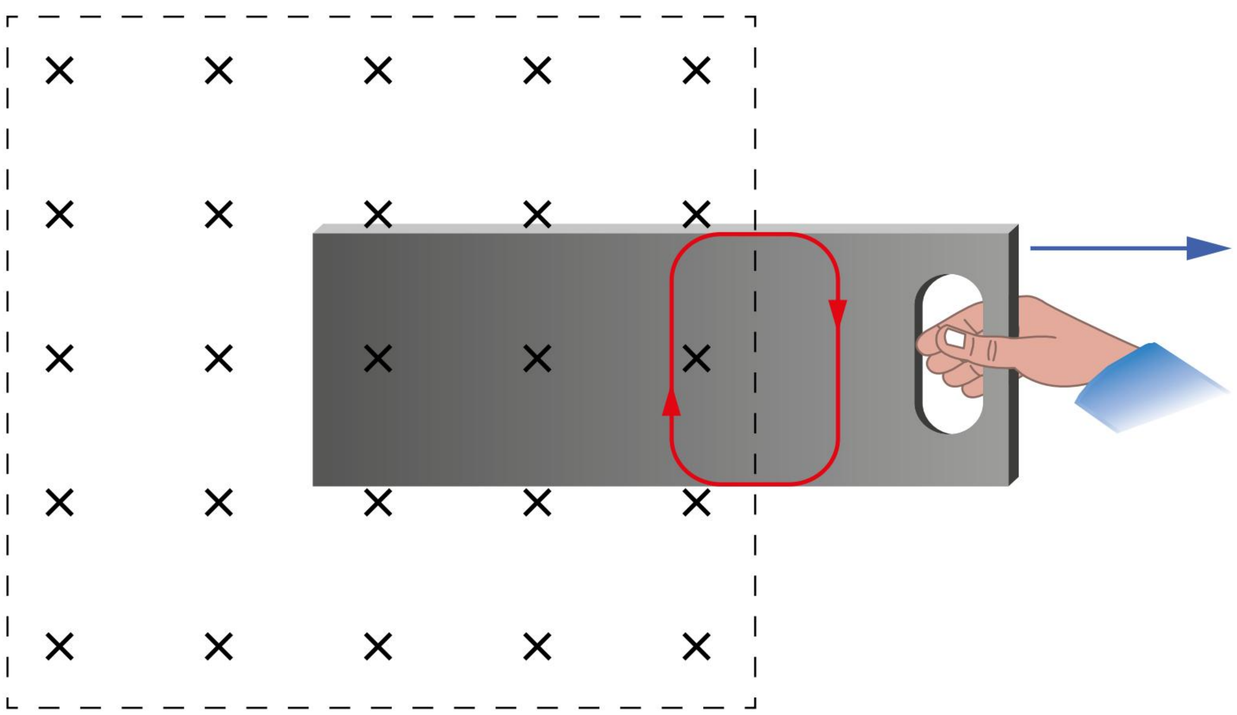


FIGURE 7.3.6 As the metal plate is moved to the right, out of the magnetic field that is directed into the page, an eddy current forms in a clockwise direction. This eddy current would resist the motion of the plate.

INDUCED EMF IN AN ALTERNATOR OR GENERATOR

A basic electric generator, or alternator, consists of many coils of wire wound on an iron core framework. This is called an armature and it is made to rotate in a magnetic field. The axle is turned by some mechanical means—mechanical energy is being converted to electrical energy—and an EMF is induced in the rotating coil.

Consider a single loop of wire in a generator (Figure 7.3.7). Initially, the plane of the area of the loop is perpendicular to the field B and the amount of flux $\phi = BA\cos\theta$ is at a maximum. The loop is then turned one quarter of a turn and is parallel to the field:

$$\phi = BA\cos 90° = 0$$

As the loop continues to turn, the flux increases to a maximum but in the opposite sense relative to the loop in Figure 7.3.7a:

$$\phi = BA\cos 180° = -BA$$

The flux then decreases to zero again as the loop is parallel to the field:

$$\phi = BA\cos 270° = 0$$

before repeating the cycle again from (e) onwards. It is this change in flux that induces the EMF.

Lenz's law tells you that as the flux in the loop decreases from position (a) to (b) in Figure 7.3.7, the induced current will be in a direction such as to restore a magnetic field in the same direction, relative to the loop, as the external field. The right-hand grip rule can be used to show that the direction of the induced current will be D → C → B → A.

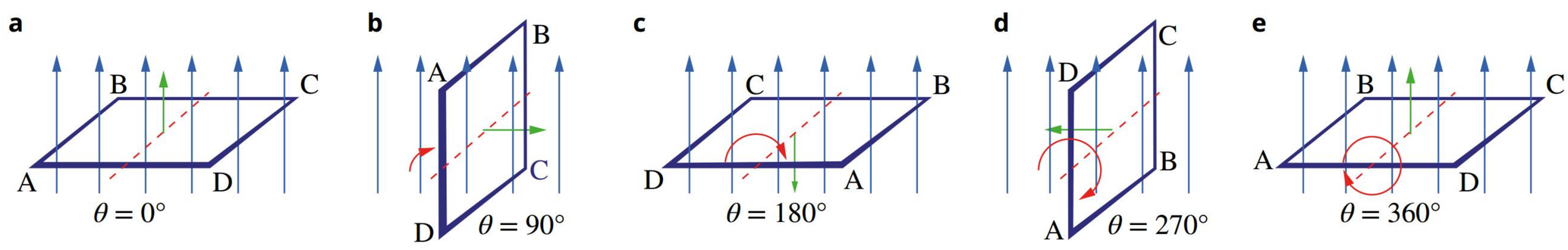


FIGURE 7.3.7 A single loop of wire, in a uniform magnetic field B, is rotated clockwise, at constant speed. The amount of flux threading through the loop will vary as it rotates.

The direction of the induced current will reverse every time the plane of the loop reaches a point perpendicular to the field. The magnitude of the induced EMF will be determined by the rate at which the loop is rotating, according to Faraday's law. It will be a maximum when the rate of change of flux is a maximum.

This is when the loop has moved to a position parallel to the magnetic field and the flux through the loop is zero, that is, the gradient of the graph of flux versus angle shown in Figure 7.3.8 is a maximum. Note that this graph can also be construed as flux versus time, as the speed of rotation is constant.

An alternative way to think about how the EMF changes as the loop rotates is to remember that the EMF is created as the wires AB and CD cut across the magnetic field lines. Maximum EMF occurs when these wires cut the magnetic field lines perpendicularly, when θ is 90° or 270°, and zero EMF occurs when the motion of these wires is parallel to the field lines, that is, when θ is 0°, 180° or 360°.

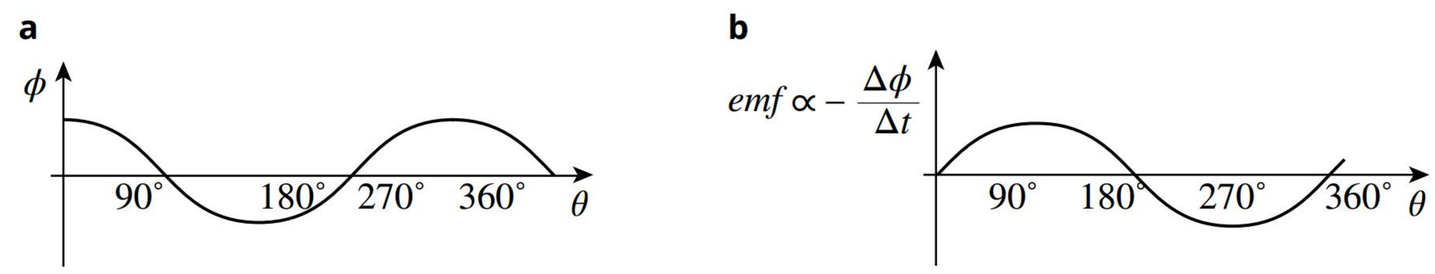


FIGURE 7.3.8 (a) The flux, ϕ, through the loop of Figure 7.3.7 is a function of the angle between the field and the normal to the plane of the area, θ. (b) The rate of change of flux and hence EMF through the loop is a function of the angle between the field and the normal to the plane of the loop, θ. The loop is rotating at a constant speed.

7.3 Review

SUMMARY

- Lenz's law states that the direction of an induced current is such that it will always oppose the change in flux that created it.
- There are three distinct steps to determine the induced current direction according to Lenz's law:
  1 What is the change in flux that is happening?
  2 What will oppose this change in flux?
  3 What must be the direction of the current that would match this opposition?
- A coil rotated in a magnetic field will produce an alternating induced current in the coil, with voltage and current varying as a sine wave.

KEY QUESTIONS

Describe

1 Recall the meaning of the negative sign in Faraday's law.

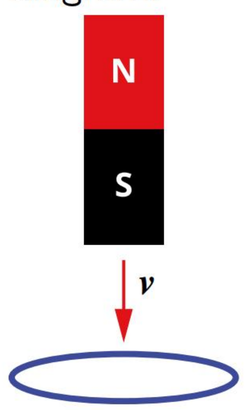
2 Recall the law of the conservation of energy.

3 The north pole of a magnet moves left towards a loop. Identify whether the magnetic flux to the left increases or decreases.

4 Identify whether the magnitude of the induced EMF will be at maximum or minimum when the rate of change of flux is a maximum.

Apply

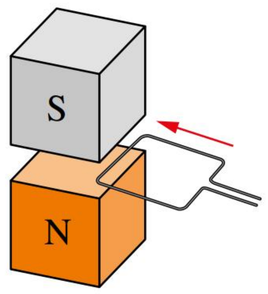
5 A magnet moves downwards towards a coil as in the diagram.



a Describe the direction of the induced current in the coil.

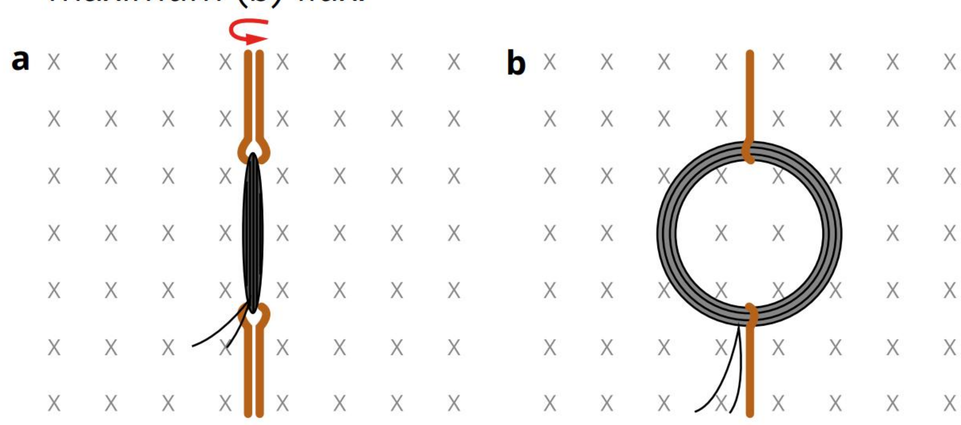
b Explain how energy is conserved in this scenario. If the law of conservation of energy was violated, what difference would this make to your answer for part **a**?

6 Imagine that a wire coil is inserted into a magnetic field as shown below.



- **a** Describe the direction of the initial flux threading the square loop.
- **b** Describe the direction of the flux threading the loop, once it has been inserted into the field.
- **c** Determine the direction of the change in magnetic flux through the loop.
- **d** Determine the direction of the flux created by the induced EMF.
- **e** Determine the direction of the induced current in the loop.

7 Consider a coil rotating in a magnetic field, as in the diagram below. The coil is rotating anticlockwise when viewed from above, from a position of minimum (a) to maximum (b) flux.



- **a** Determine the direction of the initial flux threading the loop.
- **b** Determine the direction of the flux threading the loop in its final position.
- **c** Determine the direction of the change in magnetic flux through the loop.
- **d** Determine the direction of the induced current in the loop.

8 Explain when an eddy current is produced.

9 According to Lenz's law, the magnitude of induced EMF is at a maximum when the rate of change of magnetic flux is at a maximum. This corresponds to the points of maximum gradient on a flux–time graph. Identify from Figure 7.3.8 on page 174 the angles of rotation for which this gradient is a maximum.

10 Assume that an anticlockwise rotation of a coil starting from $\theta = 0°$ perpendicular to a constant magnetic field initially produces a positive current. Draw a graph that best illustrates the variation in the induced EMF as a function of time for one full revolution of the coil.

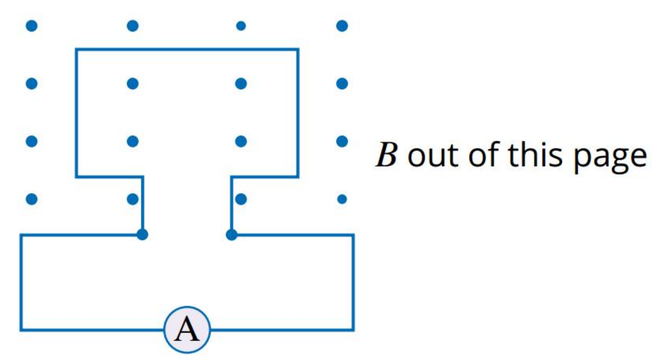
Analyse

11 A student conducts an investigation to find a relationship of the induced emf of a rotating coil.

- **a** What are the variables of this investigation?
- **b** They produce a graph of their results. Predict the expected shape of the graph.

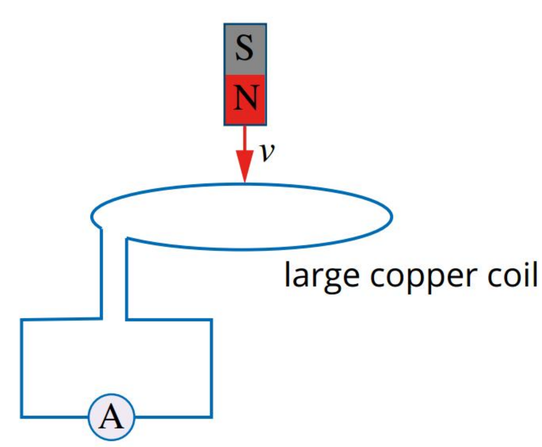
12 A rectangular conducting loop forms the circuit shown below. The plane of the loop is perpendicular to an external magnetic field whose magnitude and direction can be varied. The initial direction of the field is out of the page.

- **a** Deduce the direction of the magnetic field due to the induced current when the magnetic field is switched off.
- **b** Determine the direction of the magnetic field due to the induced current when the direction of the magnetic field is reversed.

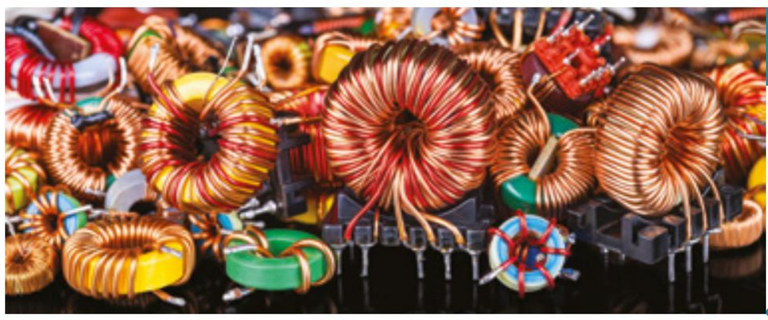


13 A bar magnet is falling towards the centre of a horizontal copper coil, as shown below.

- **a** Determine the direction (as seen from above) of the induced current in the coil when the magnet is in the position shown in the diagram.
- **b** Identify four factors that would influence the magnitude of the induced current in the copper coil.



7.4 Transformers



BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- explain how transformers work in terms of Faraday's law and electromagnetic induction
- solve problems using the transformer equations.

A **transformer** works on the principle of a changing magnetic flux inducing an EMF. No matter what the size or application, a transformer will consist of two coils known as the primary and secondary coils. The changing flux originates with the **alternating current (AC)** supplied to the primary coil. The changing magnetic flux is directed to the secondary coil where it will induce an EMF in that coil (Figure 7.4.1). The two coils can be interwoven using insulated wire, or they can be linked by a soft iron core.

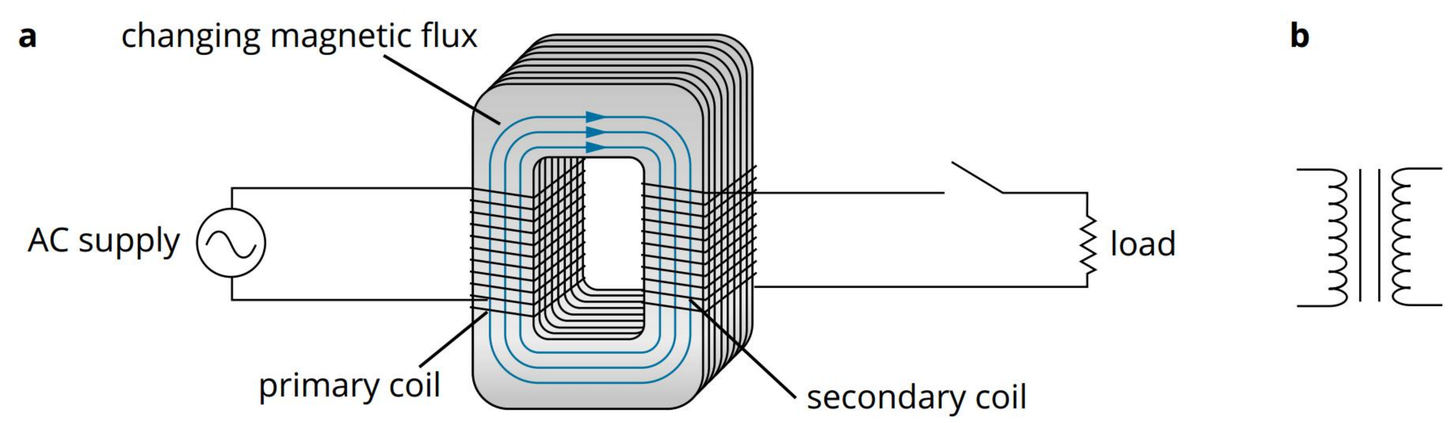


FIGURE 7.4.1 (a) In an ideal transformer, the iron core ensures that all the flux generated in the primary coil also passes through the secondary coil. (b) The symbol used in circuit diagrams for an iron-core transformer.

TRANSFORMER EFFICIENCY

As discussed in Module 7.3, eddy currents are induced in the conducting iron core of transformers that experience a changing magnetic field. Eddy currents generate a considerable amount of heat, which reduces the efficiency of the transformer and could make the device a fire hazard. To reduce losses due to eddy currents the core is separated into layers called laminations. These laminations are formed of layers of insulated iron placed in an arrangement which interrupts the eddy currents. Transformers are designed so that nearly all of the magnetic flux produced by the primary coil will pass through the secondary coil. In an **ideal transformer**, the assumption is that this will be 100% efficient and energy losses can be ignored. In a real transformer, this assumption remains a good approximation. Transformers are one of the most efficient devices around, with practical efficiencies often being better than 99%.

AC VERSUS DC

A power distribution system works on alternating current. That may seem odd when many devices run on direct current, but one of the primary reasons is the ease with which alternating current can be transformed from one voltage to another.

A transformer works based on a changing current in the primary coil inducing a changing magnetic flux. This in turn induces a current in the secondary coil. For this to work, the original current must be constantly changing, as it does in an AC supply.

A DC voltage has a constant, unchanging current. With no change in the size of the current, no changing magnetic flux will be created by the primary coil and, hence, no current is induced in the secondary coil. Transformers do not work with

the constant current of a DC electrical supply. There will be a very brief induced current when a DC supply is turned on, and a change occurs from zero current to the supply level. There is a similar spike if the DC supply is switched off, but while the DC supply is constant there is no change in magnetic flux to induce a current in the secondary coil. You can use Faraday's law to show this. As $emf = -N\frac{\Delta\phi}{\Delta t}$, when there is no change in the magnetic flux over a period of time Δt, the formula becomes $emf = -N\frac{0}{\Delta t} = 0$.

THE TRANSFORMER EQUATION

When an AC voltage is connected to the primary coil of a transformer, the changing magnetic field will induce an AC voltage of the same frequency as the original supply in the secondary coil. The voltage in the secondary coil will be different and depends upon the number of turns in each coil.

Assuming that there is little or no loss of flux between the primary and secondary coil, then the flux in each will be the same. Using Faradays' law, you can find a ratio of the voltages for each coil.

The transformer equation, relating a voltage (V) and number of turns (N) in each coil, is:

$$\frac{V_p}{V_s} = \frac{N_p}{N_s}$$

where the subscript 'p' refers to the primary or first coil, and the subscript 's' refers to the secondary coil.

The transformer equation explains how the secondary (output) voltage is related to the primary (input) voltage. A **step-up transformer** increases the secondary voltage compared with the primary voltage. The secondary voltage is greater than the primary voltage and this is because the number of turns in the secondary coil is greater than the number of turns in the primary coil: if $N_s > N_p$ then $V_s > V_p$.

A **step-down transformer** decreases the secondary voltage compared with the primary voltage. The secondary voltage is less than the primary voltage because the number of turns in the secondary coil is less than the number of turns in the primary coil: if $N_s < N_p$ then $V_s < V_p$.

When using the transformer equation, N is the number of turns in each coil of the transformer.

Don't confuse this with the magnetic field of a solenoid where n is the number of loops per metre.

Worked example 7.4.1

TRANSFORMER EQUATION—VOLTAGE

A transformer is built into a portable radio to reduce the 240 V supply voltage to the required 12 V for the radio. Calculate the number of turns required in the primary coil if the number of turns in the secondary coil is exactly 100.

Thinking	Working
State the relevant quantities given in the question.	$V_s = 12\,V$ $V_p = 240\,V$ $N_s = 100$ turns $N_p = ?$
Substitute the quantities into the equation, rearrange and solve for N_p.	$\frac{V_p}{V_s} = \frac{N_p}{N_s}$ $\frac{240}{12} = \frac{N_p}{100}$ $N_p = 100 \times \frac{240}{12}$ = exactly 2000 turns

➤ Try yourself 7.4.1

TRANSFORMER EQUATION—VOLTAGE

A transformer is built into a phone charger to reduce the 240 V supply voltage to the required 6 V. Calculate the number of turns required in the primary coil if the number of turns in the secondary coil is 100.

POWER OUTPUT

Although a transformer very effectively increases or decreases an AC voltage, energy conservation means that the output power cannot be any greater than the input power. Since a well-designed transformer with a laminated core can be more than 99% efficient, the power input can be considered equal to the power output, making it an 'ideal' transformer.

As power supplied is $P = VI$, then:

$$I_p V_p = I_s V_s$$

Worked example 7.4.2

TRANSFORMER EQUATION—CURRENT

The secondary coil of the transformer of a radio with 2000 turns in the primary coil and 100 turns in its secondary coil draws a current of 4.0 A. Calculate the current in the primary coil.

Thinking	Working
State the relevant quantities given in the question.	$I_s = 4.0\,\text{A}$ $N_s = 100$ turns $N_p = 2000$ turns $I_p = ?$
Combine and rearrange the transformer equations to solve for the unknown variable.	$I_p V_p = I_s V_s$ $\frac{V_p}{V_s} = \frac{N_p}{N_s}$ $\therefore \frac{I_p}{I_s} = \frac{N_s}{N_p}$
Substitute the quantities into the equation, rearrange and solve for I_p.	$\frac{I_p}{I_s} = \frac{N_s}{N_p}$ $\frac{I_p}{4.0} = \frac{100}{2000}$ $I_p = 4.0 \times \frac{100}{2000}$ $= 0.20\,\text{A}$

➤ Try yourself 7.4.2

TRANSFORMER EQUATION—CURRENT

A phone charger with 4000 turns in its primary coil and 100 turns in its secondary coil draws a current of 0.50 A. Calculate the current in the primary coil.

Worked example 7.4.3

TRANSFORMERS—POWER

The power drawn from the secondary coil of the transformer by a portable radio is 48 W. Determine what power is drawn from the mains supply if the transformer is an ideal transformer.	
Thinking	**Working**
The energy efficiency of a transformer can be assumed to be 100%. The power in the secondary coil will be the same as that in the primary coil.	The power drawn from the mains supply is the power in the primary coil, which will be the same as the power in the secondary coil: $P = 48\,\text{W}$.

➤ Try yourself 7.4.3

TRANSFORMERS—POWER

The power drawn from the secondary coil of the transformer in a phone charger is 3 W. Determine the power drawn from the mains supply if the transformer is an ideal transformer.

7.4 Review

SUMMARY

- A transformer works on the principle that a changing magnetic flux induces an EMF. No matter what the size or application, it will consist of two coils, known as the primary and secondary coils.
- Ideal transformers are 100% efficient; real transformers are often more than 99% efficient, and for this reason power losses within the transformer can be ignored in calculations.
- The transformer equation can be written in different versions, but is based on:

$$\frac{V_p}{V_s} = \frac{N_p}{N_s}$$

- N is the number of turns in each coil of the transformer.
- A step-up transformer increases the secondary voltage compared with the primary voltage.
- A step-down transformer decreases the secondary voltage compared with the primary voltage.
- The transformer equation can also be written in terms of current:

$$I_pV_p = I_sV_s$$

KEY QUESTIONS

Describe

1. Describe a transformer.
2. Identify the percentage efficiency of an ideal transformer.
3. State the transformer equation linking primary and secondary voltages to the number of turns on the primary and secondary coils.

Apply

4. The secondary coil of the transformer with 1750 turns in the primary coil and 200 turns in its secondary coil draws a current of 4.3 A. Calculate the current in the primary coil.
5. A transformer is built to reduce the 240 V supply voltage to the required 14 V for an appliance. Calculate the number of turns required in the primary coil if the number of turns in the secondary coil is 50.

7.4 Review *continued*

6 A transformer with 200 turns in the primary coil and 1000 turns in the secondary coil is used to transform a primary voltage of 50 V. Calculate the secondary voltage in this setup.

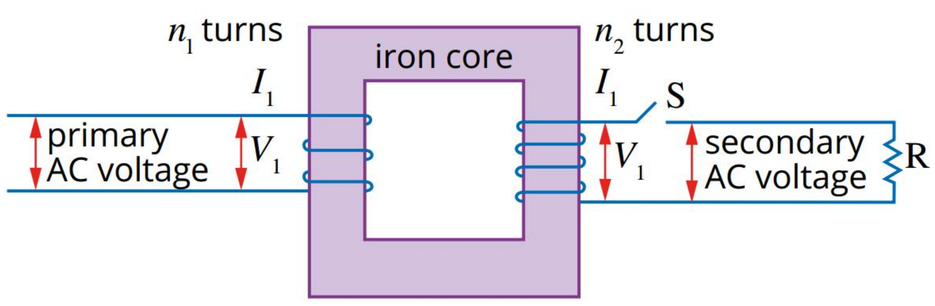
7 Describe how a transformer works.

8 **a** Identify where eddy currents are created in a transformer.

b Describe how the part of the transformer identified in part **a** is constructed in order to minimise the production of eddy currents.

9 Explain why a transformer will only operate using AC voltage and not DC voltage.

10 The figure below depicts an iron core transformer. An alternating voltage applied to the primary coil produces a changing magnetic flux. The secondary circuit contains a switch, S, in series with a resistor, *R*. The number of turns in the primary coil is N_1 and in the secondary N_2. The power in the first coil is P_1 and that in the second coil P_2. Assume that this is an ideal transformer.



a Express the relationship between the power in the primary coil, P_1, and the power in the secondary coil, P_2, with an equation.

b Express the relationship between the current in the secondary coil, I_2, and the current in the primary coil, I_1, in terms of the number of turns in each coil, with an equation.

Analyse

11 A student conducts an experiment to investigate changing the number of turns and the effect on the measured potential difference. They collect the following data.

N_p	N_s	V_p (V)	V_s (V)	$\frac{V_p}{V_s}$	$\frac{N_p}{N_s}$
240	240	8.3	7.9		1
240	120	8.2	4.0		2
120	120	8.3	8.0		1
120	240	8.1	15.7		0.5

a Categorise each row as a step up or step-down transformers.

b Comment on whether the results support the transformer equation.

$$\frac{V_p}{V_s} = \frac{N_p}{N_s}$$

12 The primary windings of a transformer consist of exactly 20 turns and the secondary of exactly 200 turns. The primary voltage input is 8.0 V and a primary current of 2.0 A is flowing.

a Determine the voltage across the load attached to the secondary coil.

b Calculate how much power is being supplied to the load attached to the secondary coil.

c Calculate the current in the secondary coil.

13 A security light is connected to a mains voltage of 240.0 V. It runs on a voltage of 12.0 V and a current of 2.0 A. A step-down transformer with exactly 800 turns on the primary winding is used to reduce the voltage from the mains level to the required operating voltage. Assume that the light is operating normally and that there is no power loss in the transformer.

a Calculate the number of turns, to the nearest whole number, in the secondary coil.

b Calculate the value of the current in the primary coil.

c Calculate the power input to the primary coil of the transformer.

d During some routine maintenance work, the primary coil of the transformer for the security light is unplugged from the AC mains supply and plugged into a DC supply of 240.0 V instead. Determine the new output (secondary) voltage.

7.5 Electromagnetic radiation

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- understand that light is an electromagnetic wave and can travel through a vacuum
- describe the concept of an electromagnetic wave
- explain how an oscillating charge induces a magnetic field and produces a self-propagating electromagnetic wave
- use the wave equation to find the frequency or wavelength of electromagnetic radiation.

In this chapter it has been shown that electric current can be used to produce a magnetic field and a changing magnetic field can be used to generate an electromotive force (EMF) or voltage. In the middle of the 19th century, the Scottish physicist James Clerk Maxwell used this knowledge to gain a key insight into the nature of light waves. In his mathematical study of electric and magnetic effects, he realised that some of the constants in his equations closely matched the current estimates of the speed of light. Maxwell went on to develop a comprehensive theory of electromagnetism in which light is a form of **electromagnetic radiation (EMR)** (Figure 7.5.1).

FIGURE 7.5.1 Light is a form of electromagnetic radiation.

OSCILLATING CHARGES

In Chapter 6, it was shown that a magnetic field is generated perpendicular to a moving electric charge. James Clerk Maxwell proposed that if a changing electric field is produced, for example by a charged particle moving backwards and forwards (vibrating or oscillating), then this changing electric field will produce a changing magnetic field at right angles to the electric field (Figure 7.5.2).

The changing magnetic field would, in turn, produce a changing electric field and the cycle would be repeated. In effect, this would produce two mutually propagating fields and the electromagnetic radiation would be self-propagating—it could extend outwards into space. Both the electric and magnetic fields would oscillate at the same frequency: the frequency of the light wave.

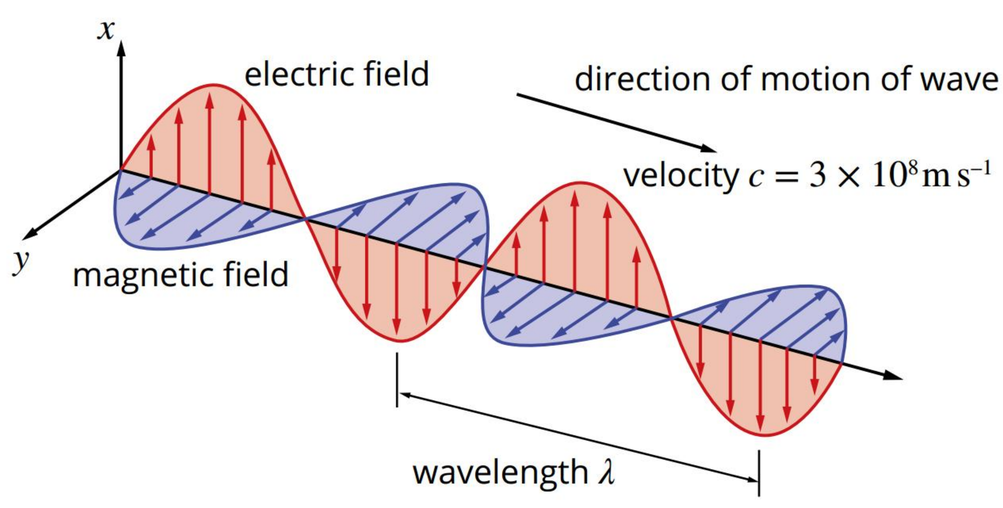


FIGURE 7.5.2 The electric and magnetic fields in electromagnetic radiation are perpendicular to each other and both are perpendicular to the direction of propagation of the radiation.

Antennas

An example of an oscillating charge can be found in a radio transmitter. The transmitter converts the signal (such as a radio announcer's voice, music or stream of data) into an alternating current. When this alternating current flows in the transmission antenna, the electrons in the antenna oscillate backwards and forwards. This oscillation of charges in the antenna produces a corresponding electromagnetic wave that radiates outwards in all directions from the antenna.

When the radio wave hits the antenna of a radio receiver, the electrons in the receiver's antenna start to oscillate in exactly the same way as in the transmitting antenna. The radio receiver then reverses the process of the transmitter, converting the alternating current from the reception antenna back into the original signal (Figure 7.5.3).

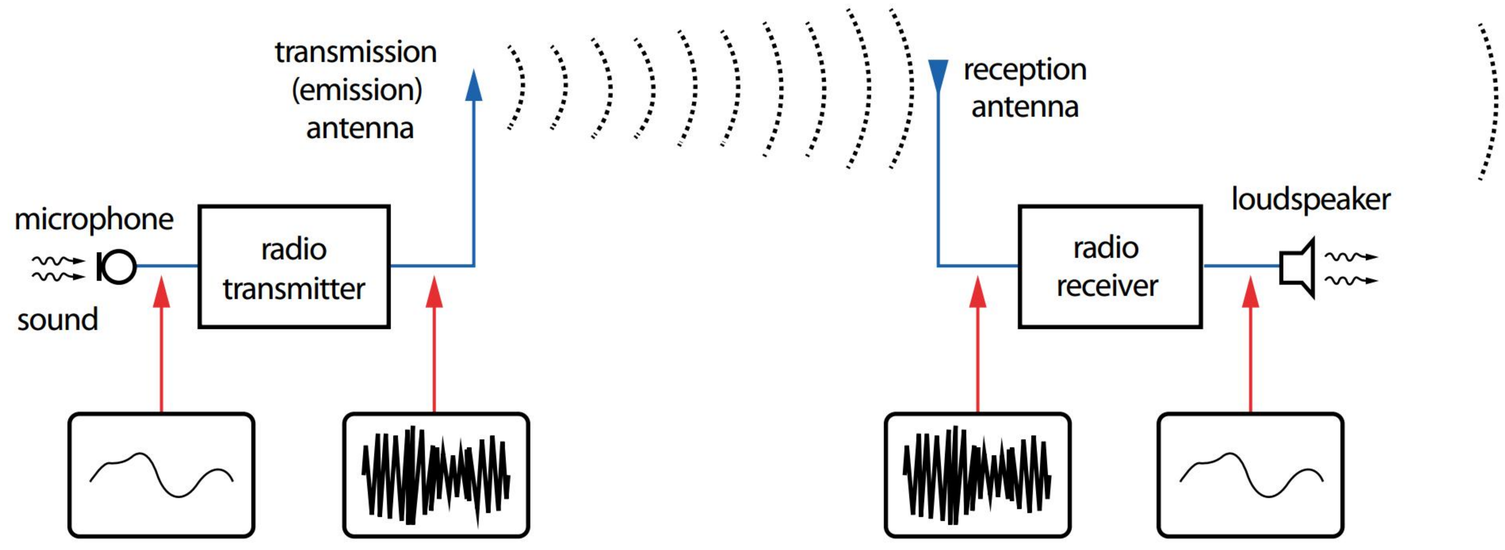


FIGURE 7.5.3 A typical radio transmission system

THE ELECTROMAGNETIC SPECTRUM

Recall from *Pearson Physics Queensland Units 1 & 2* that the electromagnetic (EM) spectrum is roughly divided into seven categories, depending on how the radiation is produced and the frequency of the waves (Figure 7.5.4). These boundaries shouldn't be thought of as exact, but they do provide a convenient means of identifying the properties of the EMR in each section.

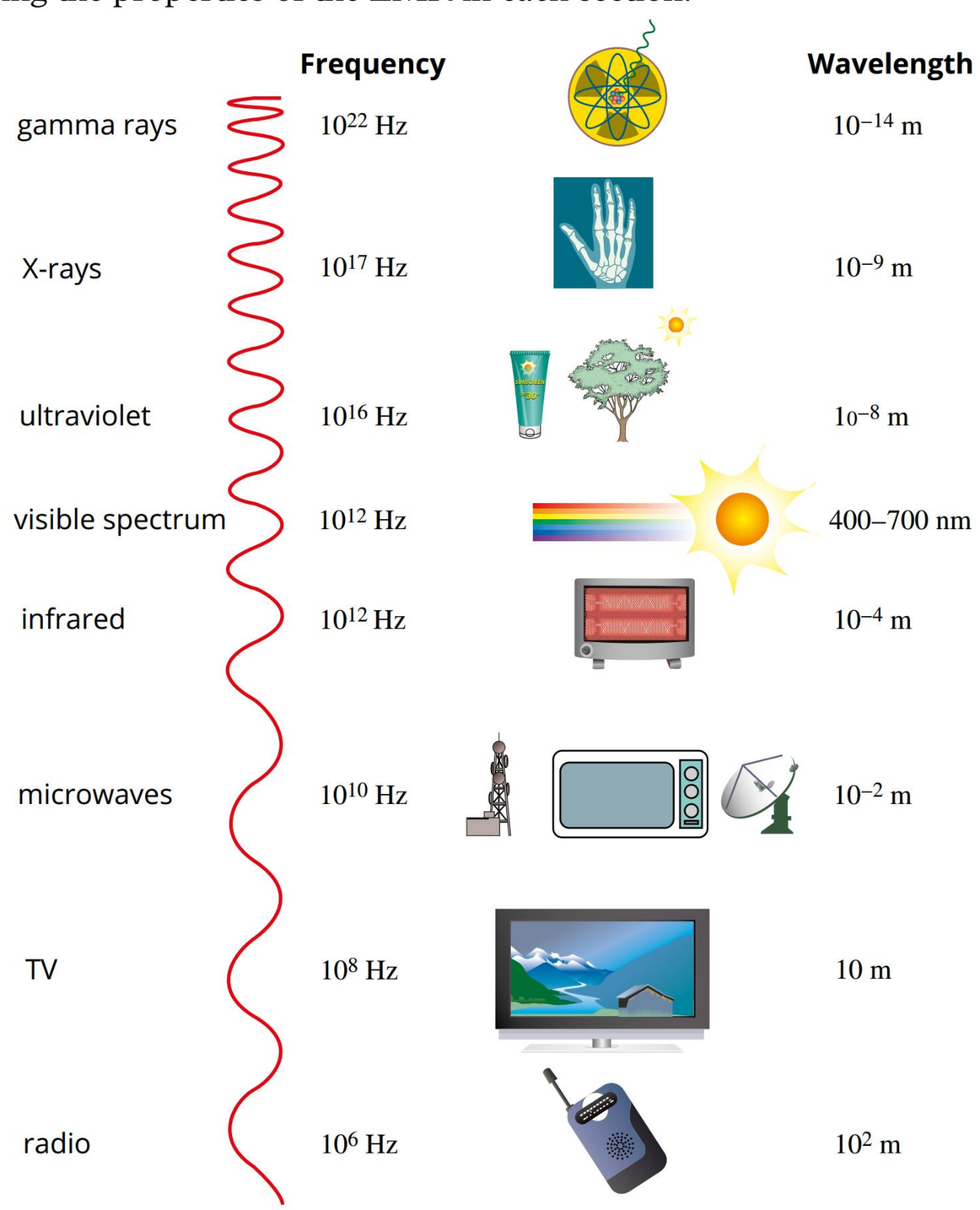


FIGURE 7.5.4 In this representation of the electromagnetic spectrum, the radio wave section of the spectrum is broken down into two sections: television and radio.

THE WAVE EQUATION

The familiar wave equation that you studied in *Pearson Physics Queensland Units 1 & 2* is $v = f\lambda$, which relates the frequency (f), wavelength (λ) and speed (v) of the wave. For electromagnetic radiation, the frequency of the oscillating charge is equal to the frequency of the produced electromagnetic wave. You can then use this relationship to analyse the features of different EMR waves.

Maxwell's theoretical calculations provided a value for the speed at which EMR should propagate through empty space. This matched the experimental value for the speed of light measured by the French physicist Hippolyte Fizeau in 1849. The accepted defined value for the speed of light today is $299\,792\,458\,\mathrm{m\,s^{-1}}$. This is such an important constant that it is designated its own symbol, c. In calculations, the speed of light is usually approximated as $c = 3 \times 10^8\,\mathrm{m\,s^{-1}}$.

For light and other forms of EMR the wave equation is usually written as:

$c = f\lambda$

where

f is the frequency of the wave in hertz (Hz)

λ is the wavelength of the wave in metres (m).

Worked example 7.5.1

USING THE WAVE EQUATION FOR EMR

Calculate the frequency of violet light within the electromagnetic spectrum with a wavelength of 400.0 nm (400.0×10^{-9} m).	
Thinking	**Working**
Recall the wave equation for light.	$c = f\lambda$
Transpose the equation to make frequency the subject.	$f = \frac{c}{\lambda}$
Substitute in values to determine the frequency of this wavelength of light.	$f = \frac{3 \times 10^8}{400 \times 10^{-9}}$ $= 7.50 \times 10^{14}\,\mathrm{Hz}$

➤ Try yourself 7.5.1

USING THE WAVE EQUATION FOR EMR

A particular colour of red light within the electromagnetic spectrum has a wavelength of 600.0 nm. Calculate the frequency of this wave.

7.5 Review

SUMMARY

- Light is a form of electromagnetic radiation.
- Electromagnetic waves are transverse waves made up of mutually perpendicular, oscillating electric and magnetic fields.
- Oscillating charges produce electromagnetic waves of the same frequency as the oscillation. Electromagnetic waves cause charges to oscillate at the frequency of the wave.
- All electromagnetic radiation travels through a vacuum at approximately $c = 3 \times 10^8\,\mathrm{m\,s^{-1}}$.
- The wave equation $c = f\lambda$ can be used to calculate the frequency and wavelength of electromagnetic waves.

KEY QUESTIONS

Describe

1 Recall the two types of fields that oscillate to produce an electromagnetic wave.

2 State the angle of orientation between the changing electric and magnetic fields in an electromagnetic wave.

3 How does the frequency of an oscillating charge relate to the frequency of the electromagnetic wave it produces?

4 How does the wavelength of an electromagnetic wave relate to the period of the oscillating charge that produced it?

Apply

5 Explain how it is possible for an electromagnetic wave to be self-propagating.

6 To transmit a radio signal, a radio wave is produced from an antenna.

a Identify what oscillates inside the antenna to produce this radio wave.

b Explain why these particles oscillate.

7 Determine the frequencies of the following wavelengths of light:

a red light of wavelength 656 nm

b yellow light of wavelength 589 nm.

8 An electron is oscillated 1.2 times every nanosecond. Determine the wavelength of light produced in this scenario.

Analyse

9 Although the currently defined value for the speed of light is $299\,792\,458\,\mathrm{m\,s^{-1}}$, this is often approximated as $c = 3 \times 10^8\,\mathrm{m\,s^{-1}}$. Determine the percentage error introduced by this approximation.

10 Calculate the wavelength (in nm) of an electromagnetic wave with a frequency of $6.0 \times 10^{14}\,\mathrm{Hz}$.

11 Calculate the frequency of an X-ray with a wavelength of 200.0 pm.

12 Calculate the wavelength of the electromagnetic waves produced by a microwave oven with a frequency of 2.45 GHz.

Chapter review

07

KEY TERMS

alternating current (AC)
electromagnetic induction
electromagnetic radiation
electromagnetic (EM) spectrum
electromotive force
Faraday's law of induction
ideal transformer
induced current
Lenz's law
magnetic flux
magnetic flux density
magnetic field
parallel
perpendicular
step-down transformer
step-up transformer
transformer

KEY QUESTIONS

Describe

1 Identify the scenario that will not induce an EMF in a long, straight conductor.

A A magnet is brought near the conductor.
B The conductor is brought into a magnetic field.
C A magnet is stationary alongside the conductor.
D The conductor is rotated within a magnetic field.

2 A conducting loop is located in an external magnetic field whose direction (but not necessarily magnitude) remains constant. A current is induced in the loop. Identify the best description of the direction of the magnetic field due to the induced current.

A The direction can't be determined from the information supplied.
B It will always be in the same direction as the external magnetic field.
C It will always be in the opposite direction to the external magnetic field.
D It will be in the same direction as the external magnetic field if the external magnetic field gets weaker, and it will be in the opposite direction to the external magnetic field if the external magnetic field gets stronger.

3 Identify the best description of how a transformer transfers electrical energy from the primary windings to the secondary windings. The current through the primary windings produces:

A no magnetic field in the secondary windings.
B a constant electric field in the secondary windings.
C a steady magnetic field in the secondary windings.
D a changing magnetic field in the secondary windings.

4 Identify the orientation of the changing electric and magnetic fields in an electromagnetic wave.

A They are at 45° to each other.
B They are parallel to each other.
C They are perpendicular to each other.
D They are parallel but in opposite directions.

5 Recall the proportional relationship between the change in area and the induced EMF.

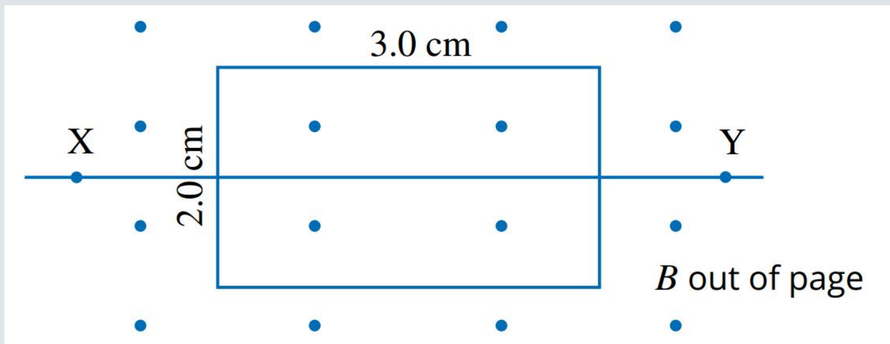
6 Identify the units of magnetic flux density?

7 Contrast Faraday's law and Lenz's law.

8 Explain how an electromagnetic wave is self-propagating?

Apply

The following information relates to Questions **9–11**.
A single rectangular wire loop is placed with its plane perpendicular to a uniform magnetic field of 2.0 mT directed out of the page, as shown below. The loop is free to rotate about a horizontal axis XY.



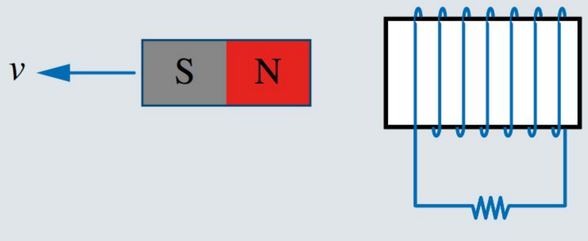
9 Determine how much magnetic flux is threading the loop in this position.

10 The loop is rotated about the axis XY through an angle of 90° so that its plane is now parallel to the magnetic field. Describe how much flux is threading the loop in this new position.

11 Calculate the average induced EMF in the loop if the loop completes one-quarter of a rotation in 40.0 ms.

12 Determine the relationship between the change in angle and the induced EMF.

13 The north pole of a magnet is moved away from a coil to observe the induced current. Predict the direction of the induced current in the coil and justify your answer.



14 An electric, current-carrying loop of $3\,cm^2$ is placed perpendicularly within a magnetic field of strength 0.5 T. Calculate the magnetic flux in the coil.

15 A magnetic field threads through a rectangular coil. Identify the best option when the flux is at a maximum angle between the normal to the coil and the field.

A 0°
B 45°
C 90°
D 180°

16 A square loop of side length 10 cm is placed inside a magnetic field of strength 0.2 T. The coil is positioned at right angles to the field. Identify which is the best option of flux threading of the coil.

A 0 Wb
B 2.0 Wb
C 0.02 Wb
D 0.002 Wb

17 Charlie and Tomin are investigating how current is generated by quickly inserting a magnet inside a coil of wire. Assume all conditions are kept the same except the variable being changed. Select which modification would not increase the EMF generated.

A Use a stronger magnet.
B Insert the magnet more slowly.
C Increase the diameter of the coils.
D Double the number of turns in the coil.

18 The power output from the secondary coil of a non-ideal transformer is slightly less than the input to the primary coil. The voltage and current in the primary coil are denoted V_1 and I_1 respectively. The voltage and current in the secondary coil are denoted V_2 and I_2 respectively. Select the power output in the secondary coil.

A $P = V_1 I_1$
B $P = V_2 I_2$
C $P = V_1 I_2$
D $P = I_2^2 R$

19 When a transformer is plugged into the 240 V mains but there is nothing connected to the secondary coil, very little power is used. Identify the best explanation for this.

A The magnetic flux generated by the secondary coil almost balances out that due to the primary coil
B There can be no magnetic flux generated in the transformer if the secondary coil has no current in it
C The magnetic flux generated by the current in the primary coil produces an EMF that opposes the applied voltage
D With nothing connected to the secondary coil, the secondary coil remains open, and no current flows.

20 Order steps X, Y and Z for the operation of a transformer.

X: A changing magnetic flux in the secondary coil induces a changing EMF.

Y: An iron core transmits the changing magnetic field from the primary coil to the secondary coil.

Z: An alternating current in the primary coil creates a changing magnetic field in the primary coil.

21 An AM radio station has a frequency of 612 kHz. Calculate the wavelength of these waves to the nearest metre if the speed of light is $3 \times 10^8\,m\,s^{-1}$.

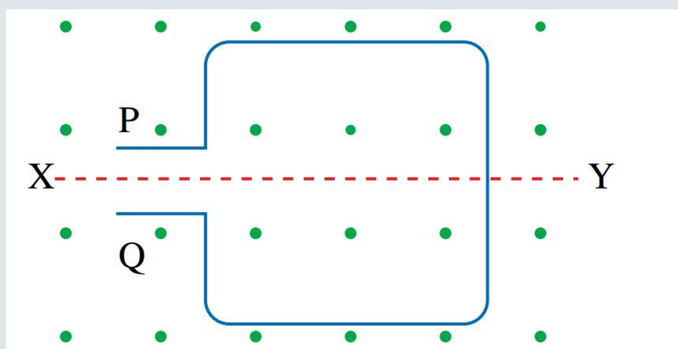
Analyse

22 Abigail has a flexible wire coil of variable area of exactly 100 turns and a strong bar magnet, which has been measured to produce a magnetic field of strength B = 100.0 mT a short distance from it. Abigail has been instructed to demonstrate electromagnetic induction by using this equipment to light up an LED rated at 1.0 V. Identify one method by which she could complete this task. Include appropriate calculations to validate your explanation.

23 A $4.5\,cm^2$ conducting coil ($N = 1$) is initially placed perpendicularly within a magnetic field of strength 0.89 T.

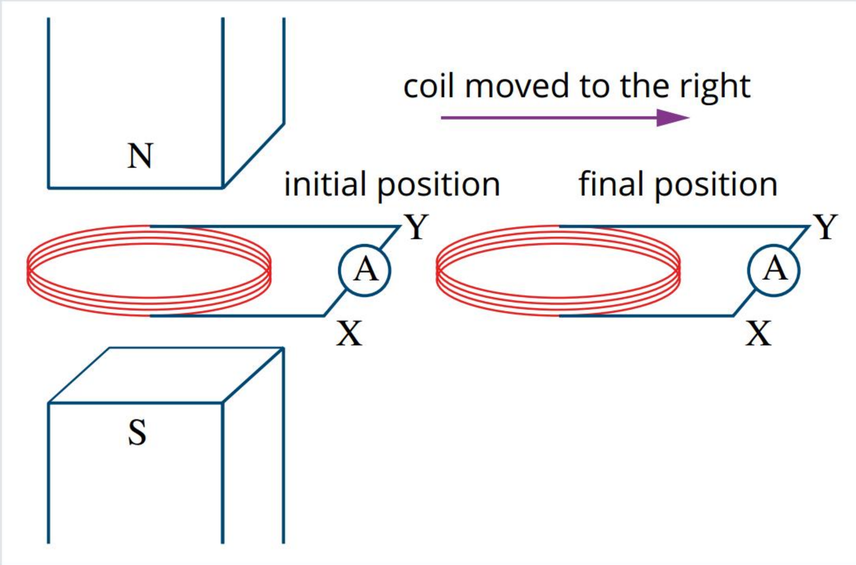
a Calculate the magnetic flux in the coil at this point.
b Calculate the induced EMF if the coil is then rotated 90° in 30 ms.
c Calculate the induced EMF if the coil is rotated a further 25° in 15 ms.

24 A rectangular coil of area $40.0\,cm^2$ and resistance 1.0 Ω is located in a uniform magnetic field $B = 8.0 \times 10^{-4}$ T that is directed out of the page. The plane of the coil is initially perpendicular to the field, as depicted in the diagram below.



a Calculate the magnitude of the EMF induced in the coil when the strength of the magnetic field is doubled in a time of 1.0 ms.
b Determine the direction of the current caused by the induced EMF in the coil when the strength of the magnetic field is doubled in a time of 1.0 ms.

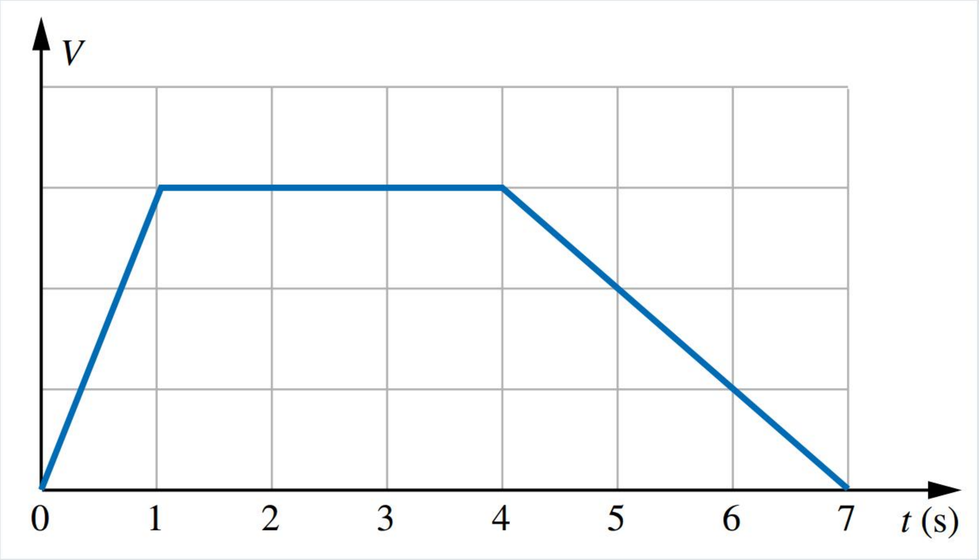
25 During a physics experiment Rhiannon pulls a horizontal circular coil from between the poles of two magnets in 0.10 s. The initial position of the coil is entirely in the field while its final position is free of the field. The coil has exactly 40 turns, each of radius 4.0 cm. The field strength between the magnets is 20.0 mT.



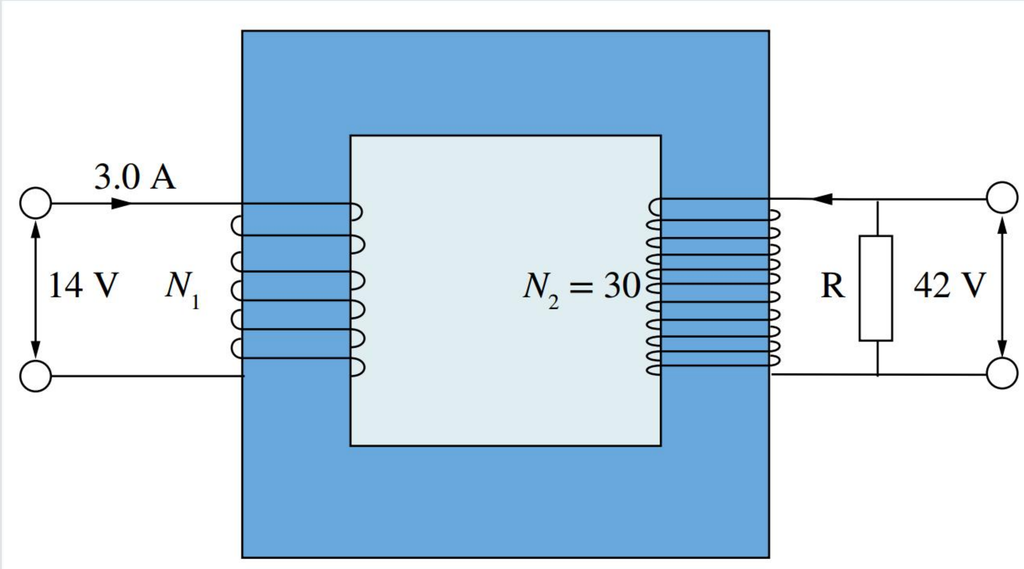
a Calculate the magnitude of the average EMF induced in the coil as it is moved from its initial position to its final position.

b Determine the direction of the current in the coil caused by the induced EMF.

26 Coils S_1 and S_2 are close together and linked by a soft iron core. The EMF in S_1 varies as shown in the graph below. Determine the shape of the variation of the current in S_2 by drawing a line graph. No calculations are required for this question.



The following information relates to Questions **27–28**.
An ideal transformer is operating with an input voltage of 14 V and primary current of 3.0 A. The output voltage is 42 V. There are exactly 30 turns in the secondary winding.



27 Determine the output current.

28 Determine the number of turns in the primary coil.

The following information refers to Questions **29–30**.
Vani builds a simple alternator consisting of a coil containing exactly 500 turns, each of area 10.0 cm^2, mounted on an axis that can rotate between the poles of a permanent magnet of strength 80.0 mT. The alternator is rotated at a frequency of 50.0 Hz.

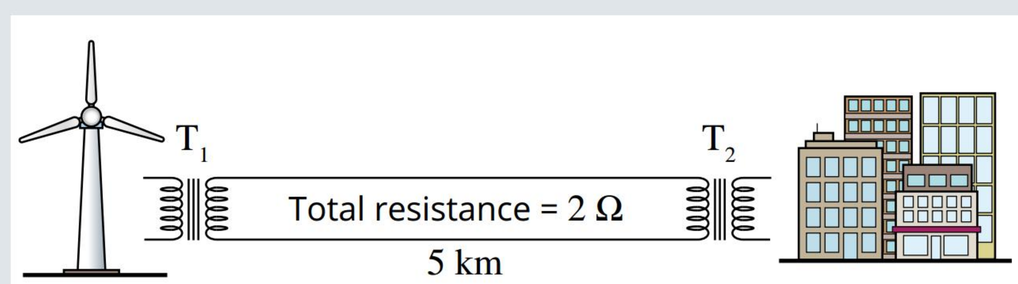
29 Calculate the EMF generated by the alternator.

30 Assess the effect on the average EMF when the frequency is doubled to 100 Hz.

Interpret

31 A generator is to be installed in a farm shed to provide 240 V power for the farmhouse. A twin-conductor power line with total resistance 8.0 Ω already exists between the shed and house. The farmer has seen a cheap 240 V DC generator advertised and is tempted to buy it.
Identify and explain two significant problems that you foresee with using the 240 V DC generator.

The following information relates to Questions **32–36**.
A wind turbine runs a 150 kW generator with an output voltage of 1000.0 V. The voltage is increased by a transformer T_1 to 10 000.0 V for transmission to a town 5.0 km away through power lines with a total resistance of 2.0 Ω. Another transformer, T_2, at the town reduces the voltage to 250 V. Assume that there is no power loss in the transformers (that is, they are 'ideal').



32 Determine the number of turns in the secondary coils if N_1,p = 500, and N_2,p = 1200.

33 Determine the current in the power lines.

34 Calculate the voltage at the input to the town transformer T_2.

35 Determine how much power is lost in the power lines.

36 It is suggested that some money could be saved from the scheme by removing the first transformer. Assess whether this is a good plan. Use appropriate calculations and include an explanation.

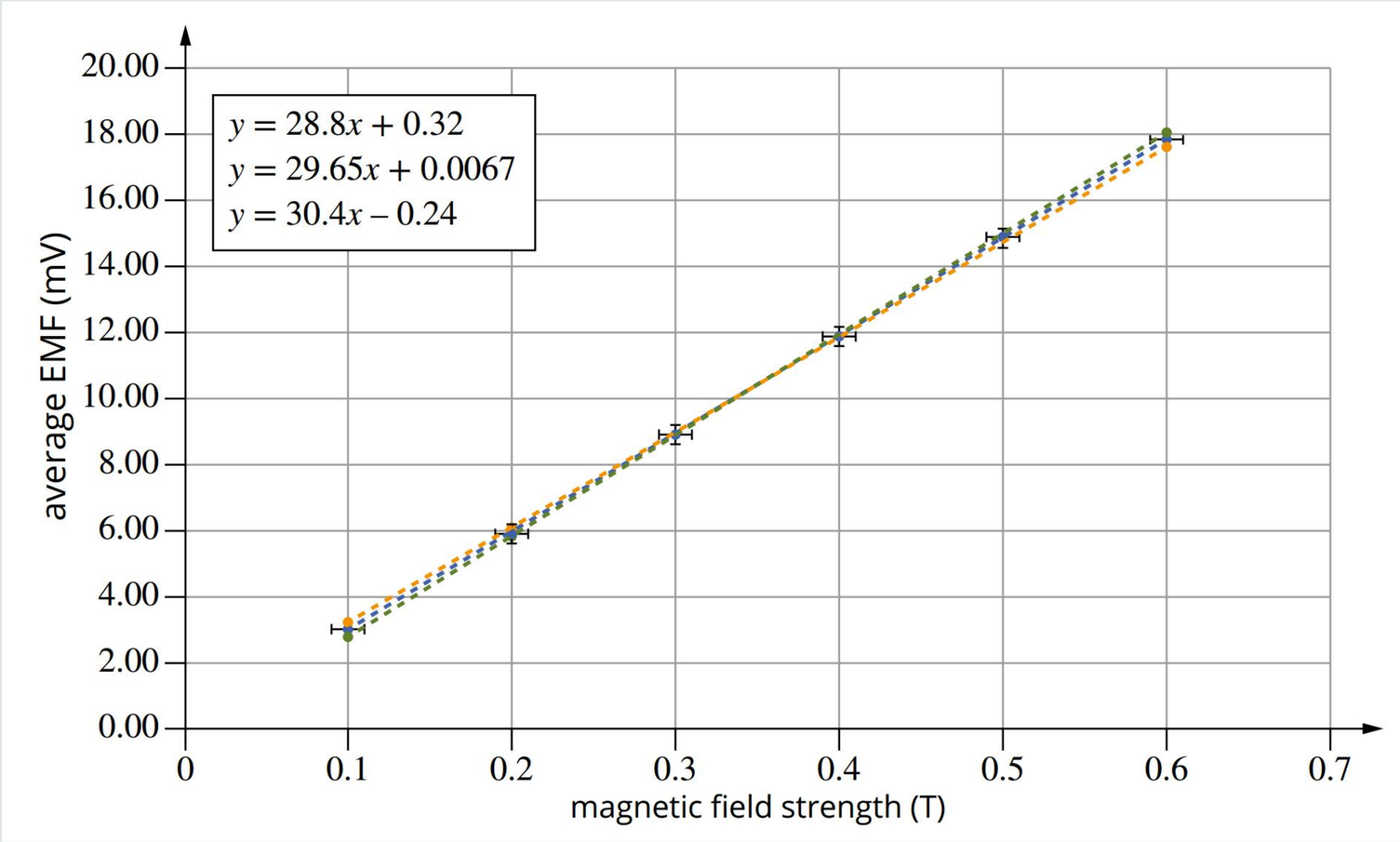
Data analysis

DATA SET 1

The information below applies to Questions **1**–**3**.

An experiment is conducted using magnets of different strengths to record the induced EMF in a fixed coil.

Magnetic field strength (T) ±0.01 T	Trial 1 EMF (mV)	Trial 2 EMF (mV)	Trial 3 EMF (mV)	Average EMF (mV)
0.1	2.8	3.2	3	3.00
0.2	5.9	6.1	5.7	5.90
0.3	8.7	9.1	8.9	8.90
0.4	11.8	12.2	11.6	11.87
0.5	14.5	15.1	14.9	14.83
0.6	17.6	18	17.8	



Question 1 (1 mark)

Calculate the missing average EMF for a magnetic field strength of 0.6 T.

Question 2 (3 marks)

Identify a mathematical relationship between the magnetic field strength and the induced EMF, including the uncertainty of the gradient and *y*-intercept.

Question 3 (1 mark)

Using the graph, extrapolate the average EMF for a magnet of strength 1.2 T using the same experimental setup.

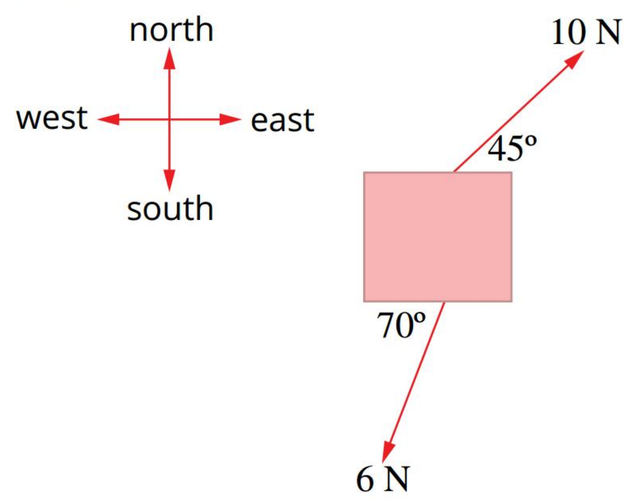
REVIEW QUESTIONS

Topic 1: Gravity and motion

Multiple choice

1 Two ropes are attached to a block on a frictionless plane as shown below, viewed from above. Identify the net force acting on the block.

A 5.3 N east
B 5.22 N N74°E
C 10.86 N north
D 5.15 N N52°E



2 A book is stationary on an inclined plane and three forces act on it: weight, friction and a normal reaction force. Identify the best description of the normal force.

A the net force in the vertical direction
B the force due to the gravitational field of Earth
C the support force acting perpendicular to the surface
D the net force in the direction perpendicular to the surface

3 A ball has been kicked at an angle of 30° from the surface at an initial velocity of $25\,m\,s^{-1}$. Identify the magnitude of the velocity of the ball at its highest point, assuming negligible air resistance.

A $25\,m\,s^{-1}$
B $12.5\,m\,s^{-1}$
C $21.7\,m\,s^{-1}$
D $10.0\,m\,s^{-1}$

4 A ball is being swung around on a string that provides a constant tension force. Initially the ball is travelling in a circular path of radius 20.0 cm with a period of 0.30 s. The string is adjusted so the ball travels in a circular path with a radius of 15.0 cm. Determine the average velocity of the ball in the new path.

A $2.05\,m\,s^{-1}$
B $3.63\,m\,s^{-1}$
C $3.95\,m\,s^{-1}$
D $2.51\,m\,s^{-1}$

5 A child on a piece of cardboard is sliding down a sand dune. The combined mass is 32 kg. The sand dune is at an angle of 35°. There is a constant frictional force of 60 N once the child starts moving. Identify the magnitude of the net force acting on the child.

A 257 N
B 197 N
C 180 N
D 120 N

6 Two students are playing on a merry-go-round. One student sits on the floor of the merry-go-round while the other student stands at the edge and pushes the merry-go-round in a circle. Identify the force(s) causing the sitting student to travel in a circle.

A the standing student pushing tangential to the circle
B the standing student pushing towards the centre of the circle
C friction between the sitting student and the floor of the merry-go-round towards the centre of the circle
D friction between the sitting student and the floor of the merry-go-round away from the centre of the circle

7 A desk fan has three blades, each 25 cm long. When on the lowest speed setting, the tips of the blades travel with a period of 0.8 s. Identify the velocity of the blade tips.

A $1.96\,m\,s^{-1}$
B $19.6\,m\,s^{-1}$
C $0.49\,m\,s^{-1}$
D $0.25\,m\,s^{-1}$

8 Select the option that correctly states the first law of planetary motion.

A The orbit of a planet is circular in shape with the Sun off centre.
B The orbit of a planet is circular in shape with the Sun in the centre.
C The orbit of a planet is elliptical in shape with the Sun in the centre.
D The orbit of a planet is elliptical in shape with the Sun at one of the foci.

9 The Cassini space probe is orbiting Jupiter. Determine a possible orbital radius and period combination. (Jupiter's mass is 1.9×10^{27} kg, Cassini's mass is 2.2×10^{3} kg.)

A $r = 6.1 \times 10^{9}$ m, $T = 107.6$ s
B $r = 6.1 \times 10^{9}$ m, $T = 8.4 \times 10^{5}$ s
C $r = 1.5 \times 10^{8}$ m, $T = 3.2 \times 10^{4}$ s
D $r = 2.3 \times 10^{9}$ m, $T = 1.9 \times 10^{5}$ s

10 Identify the correct relationship which, when combined with uniform circular motion, gives the third law of planetary motion.

A $\frac{T_a^2}{r_a^3} = \frac{T_b^2}{r_b^3}$
B $\frac{T_a^2}{r_a^3} = \frac{4\pi^2}{GM}$
C $g = \frac{GM}{r^2}$
D $F = \frac{GMm}{r^2}$

Short answer

1 At the Australia Day celebration fireworks, a rocket is launched at an angle of 85° to the horizontal.

a Calculate the initial velocity of the rocket given that it reaches a maximum height of 750 m and it starts from the ground.

b Determine the time at which the fireworks technician has set the timer so that the explosion happens at the maximum height.

2 A javelin is thrown from the hand of the athlete at an initial angle of 37° elevation, 1.7 m from the ground. It lands 3.51 s after it is let go. Calculate the initial velocity of the javelin and the horizontal distance travelled.

3 Draw a free-body diagram and calculate the magnitude of the normal force of a 200 g ball rolling down a smooth hill with an inclination of 20°.

4 Describe gravitational fields including how the behaviour of the field varies with distance.

5 A student conducting an experiment in an aeroplane uses a set of scales to measure the force of the gravitational field on a 7.500 kg object. The scales give a reading of 73.47 N.

a Calculate the strength of the gravitational field acting on the object.

b Determine the height at which the aeroplane is flying to provide the measurement taken.

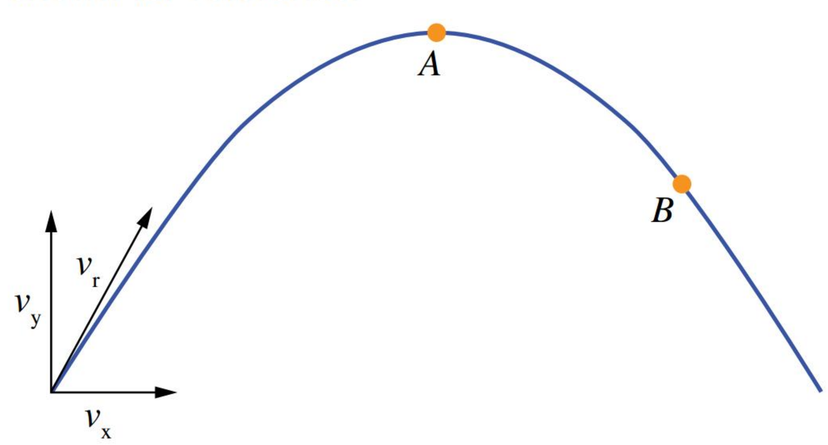
6 Astronomers investigating a newly observed planet and its moon determine the period of the moon's orbit to be 78.6 days and its orbital radius to be 5.86×10^8 m.

a Calculate the mass of the planet.

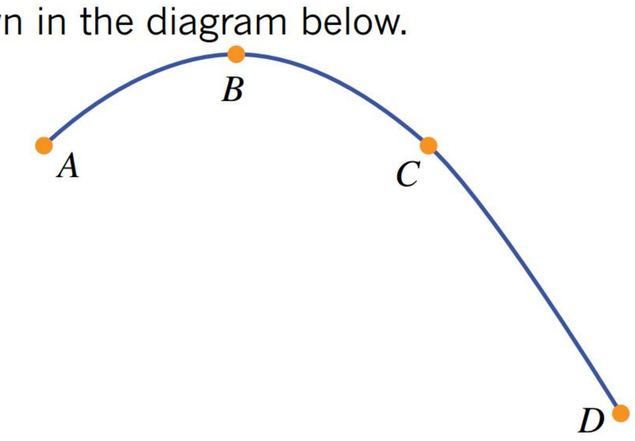
b Determine the magnitude of the average velocity with which the moon orbits the planet.

7 Chiron is a dwarf planet that orbits the Sun between Saturn and Uranus. It has an average orbital radius of 2.09×10^{12} m. Calculate the period of its orbit to the nearest year.

8 **a** A path travelled by a soccer ball kicked from rest on the ground is shown in the diagram. Draw the vectors that represent the vertical, horizontal and resultant velocity at points A and B. The initial vectors are shown for reference.



b A path travelled by a shot-put, from A to D, after it has been thrown by a competitor from a height of 1.92 m is shown in the diagram below.



Sketch a graph of the vertical component of velocity against time as the shot-put travels from the competitor's hand until it strikes the ground. Label the points A, B, C and D that correspond to these points on the curve on your graph. Other labels can be used to assist if needed.

9 A skier of mass 90 kg skis down a slope inclined at 15°. Assume the slope has negligible friction.

a Draw a free-body diagram of the skier, labelling all the forces acting on them and the appropriate angles.

b Calculate the magnitude of the normal force the skier will experience.

c Calculate the acceleration of the skier down the slope.

d Describe how the acceleration of the skier will change if they carry a pack of mass 10 kg as they travel down the same slope. Justify your answer.

10 A bucket is tied on the end of a rope of length 0.8 m that is held by a student. The student spins around, holding the end of the rope against their body, and allowing the bucket to swing out.

a Draw a free-body diagram of the forces acting on the bucket.

b Define 'centripetal acceleration' and describe the force that causes the acceleration.

c Calculate the tension force in the rope if the bucket of water weighs 1 kg, and the rope creates an angle of 20° between the student and the rope.

d Calculate the velocity of the bucket at this angle.

e Calculate the velocity and period of rotation of the bucket when the student changes the speed of the bucket so that it creates an angle of 40° to the vertical.

f The student drills a hole in the bucket so the water begins to drain. Describe how the motion of the bucket changes while the water is draining if the velocity is maintained.

11 A student conducted a practical investigation into the effect of launch angle on the horizontal distance (range) travelled by a projectile. The following results were obtained.

Angle (°)	Range (m)
10	0.61
20	0.92
30	1.10
40	1.16
45	1.17
50	1.15
60	1.05
70	0.80
80	0.35

a Create a graph of the results of the investigation.
b Use the graph to identify the relationship between angle and range.
c Predict the range of the projectile if the launch angle is increased to 90°. Justify your answer.

12 **a** Calculate the force of attraction that a 250 kg satellite orbiting Earth at a height of 36 000 km experiences from Earth's gravitational field.
b Discuss the extent to which the gravitational field of the Sun might influence the orbit of this satellite when it is between Earth and the Sun. Justify your answer with appropriate working. Note that the distance from Earth to the Sun is 1.496×10^8 km.

13 A volleyball player executes a jump-serve by running forward and jumping at an angle of 30.0° above the horizontal at a speed of $2.50\,\mathrm{m\,s^{-1}}$. After they have been in the air for 0.100 s, they launch the ball at $18.0\,\mathrm{m\,s^{-1}}$ at an angle of 12.0° above the horizontal. Determine the velocity of the ball as it leaves the player's hand, viewed by the other players on the court.

14 To play darts, the player must stand approximately 2.4 m from the target to throw their dart. Describe where the player should aim for their dart to hit the centre of the dartboard.

15 The game of darts in the previous question is modified so that as soon as the dart leaves the players hand, the dartboard falls off the wall, travelling vertically downwards. Explain how this changes where the person should aim to hit the centre of the dartboard

16 Explain why a ball thrown in low gravity would travel further horizontally than the same ball thrown in Earth's gravity. Refer to the independence of the horizontal and vertical components of motion in your response.

17 A sturdy ramp is designed to move heavy machinery into a truck. The ramp is set at an angle 15.0° to the horizontal and the surface provides a constant frictional force of 225 N. A 500 kg machine needs to be pushed up the ramp and loaded into the truck.
a Calculate the applied force required to push the machine up the ramp at a constant velocity.
b Suggest what change could be made to the placement of the ramp to make it is easier to load machinery. Explain your reasoning.
c If the ramp is kept in place and the same applied and frictional forces are applied to unload the machinery, determine the acceleration of the machine down the ramp.

18 Determine whether the average speed of an object moving in a circle ever equals the magnitude of the average velocity. Explain your answer.

19 A satellite rotates Earth in a circular path with a radius of 280 km, completing one full orbit every 90 minutes. The radius of Earth is 6400 km.
a Calculate the average speed of the satellite.
b Calculate the centripetal acceleration of the satellite.
c Determine the impact that doubling the radius would have on the velocity of the satellite if all other variables remain unchanged.

20 In August 2017, the gravitational waves produced by a pair of colliding neutron stars were recorded at two different Laser Interferometer Gravitational-Wave Observatory (LIGO) installations in the United States. The two dense stars were orbiting each other around their common centre of mass and, as they approached each other under the influence of gravity, their frequency of rotation increased. Just before they collided and formed a black hole, the frequency of rotation exceeded 1 kHz. Determine the reasons for the increasing frequency, using the third law of planetary motion.

21 Assess why the masses of Venus and Mercury, which don't have natural satellites, were more difficult to calculate.

22 In addition to the gravitational force experienced by objects on the surface of a planet, objects also experience a centripetal force due to the planet's rotation. At the equator, the Earth rotates at approximately $1656\,\mathrm{km\,h^{-1}}$ and Earth's radius is approximately 6.37×10^6 m. Calculate the centripetal acceleration experienced by a 75 kg adult standing on Earth and hence, evaluate if this value can be deemed to be negligible when calculating forces at Earth's surface.

Topic 2: Electromagnetism

Multiple choice

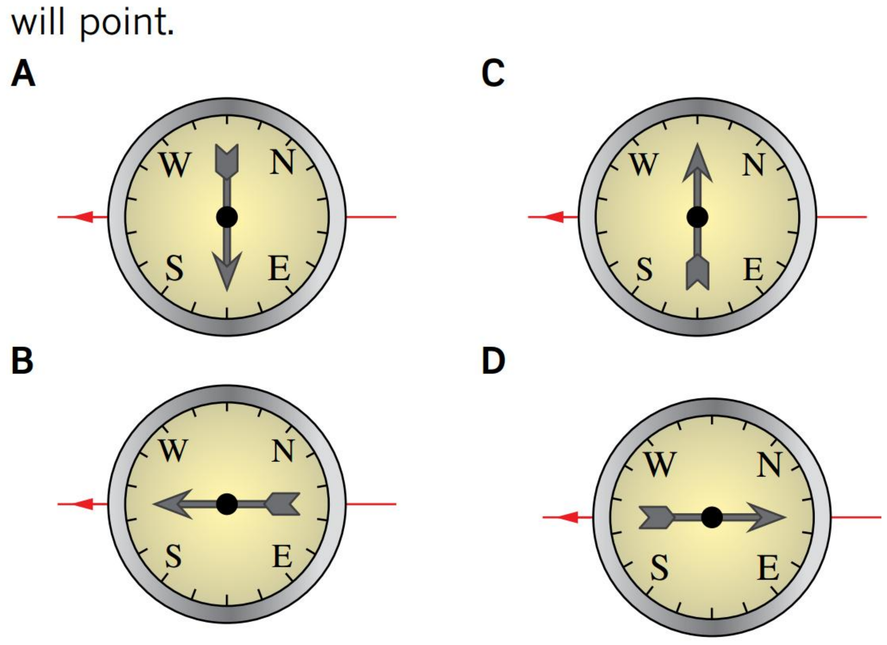
1 Select the sentence below that is not true of magnetic field lines.

A Magnetic field lines do not cross.
B Magnetic field lines must be continuous, only ending at a pole.
C Magnetic field lines go from the south pole to the north pole outside of a magnet.
D Areas where the magnetic field is stronger have field lines that are closer together.

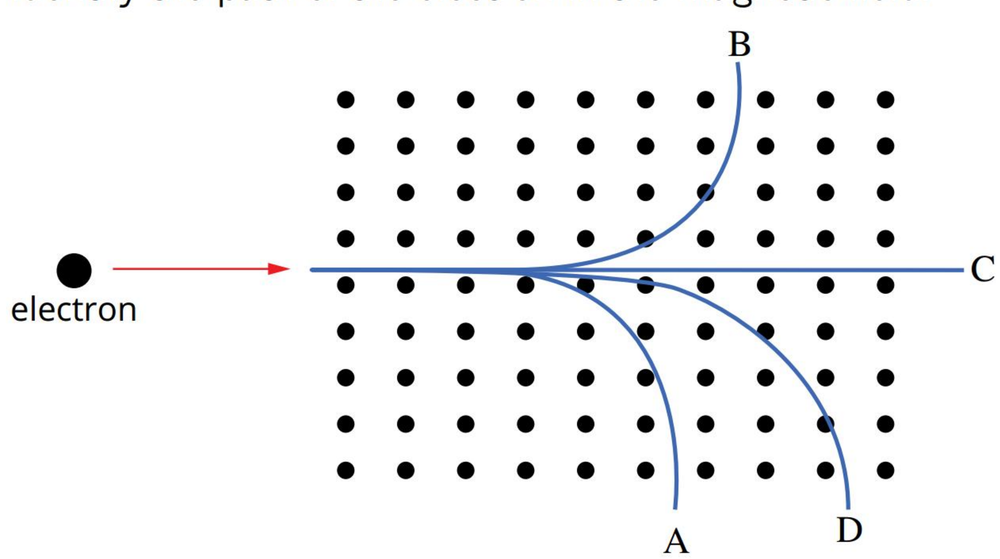
2 Two charges are held apart and exert a force of 0.1 N on each other. The charges are measured as 4.0 μC and 9.0 μC. Determine the distance between the two charges.

A 18 m
B 1.8 m
C 0.57 m
D 3.24 m

3 A compass is placed on top of a current-carrying wire. The current is in the direction from the right to the left of the page. Identify the direction in which the compass will point.



4 An electron is fired into a magnetic field as shown below. Identify the path of the electron in the magnetic field.



5 Select the most accurate description of magnetic flux.

A a region of space where a force acts on an object due to its electric charge
B the force acting per unit current per unit length on a wire placed at right angles to the magnetic field
C a region in which a moving charge or a current-carrying conductor will experience a force when it is placed in it
D a measure of the total magnetic field passing through an area calculated by multiplying the field strength by the perpendicular area

6 Select the most accurate description of electromagnetic waves from the options given.

A gamma rays from nuclear decay
B an electric and magnetic field travelling as a longitudinal wave
C parallel electric and magnetic fields travelling as a transverse wave
D perpendicular electric and magnetic fields travelling as a transverse wave

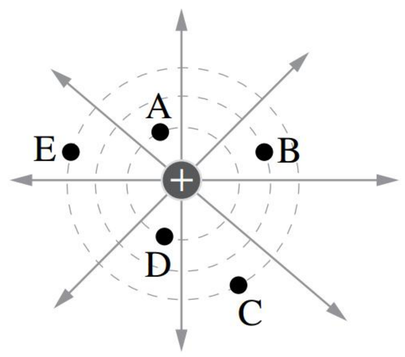
7 Select the option which most accurately describes where an alternating current is produced in a transformer.

A wire
B iron core
C primary coil
D secondary coil

8 Select the correct description of Lenz's law.

A An induced current will be created in the direction that opposes the original current.
B An induced EMF will be created that is directly proportional to the rate of change of magnetic flux.
C An induced current will be created that is directly proportional to the rate of change of magnetic flux.
D An induced EMF will be created in the direction such that the current that it causes will be in the opposite direction to the current that is causing it.

9 An electric field is created by a positive charge. The distribution of the electric field lines and equipotential lines is shown below. A test charge $+q$ is moved from point to point in the electric field. Identify which statement about work done by the electric field on charge $+q$ is true.



A Work done moving the charge from point A to B is zero.

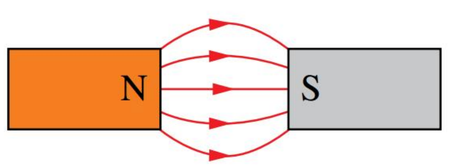
B Work done moving the charge from point A to point D is zero.

C Work done moving from point A to point B is the same as the work done moving from point C to point B.

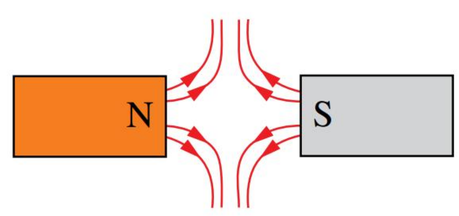
D Work done moving from point A to point B is greater than the work done moving from point A to point E.

10 Two bar magnets of equal strength are placed with the north and south poles towards each other. Identify the correct representation of the magnetic field lines that result.

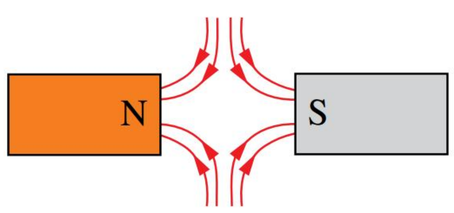
A



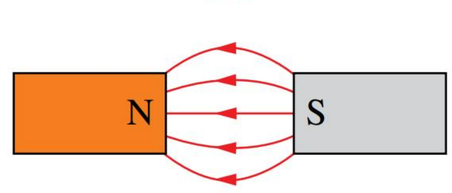
B



C

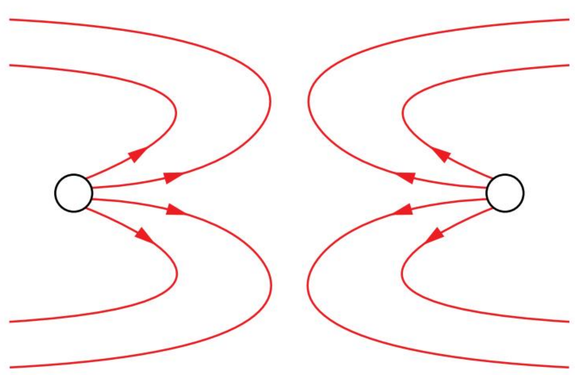


D

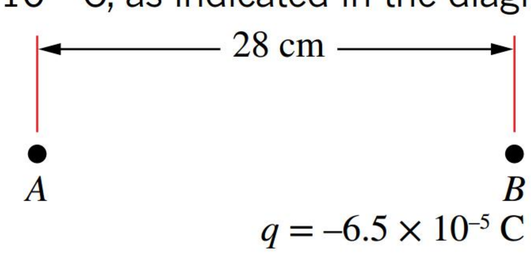


Short answer

1 Identify the charges that would result in the field lines shown.



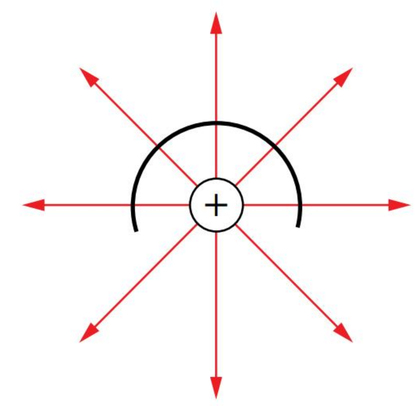
2 **a** Calculate the strength and direction of the electric field at point A 28 cm from point B, which has a charge $q = -6.5 \times 10^{-5}$ C, as indicated in the diagram below.



b A charged particle with $q = 2.4 \times 10^{-6}$ C is placed at point A. Calculate the force on the particle at point A.

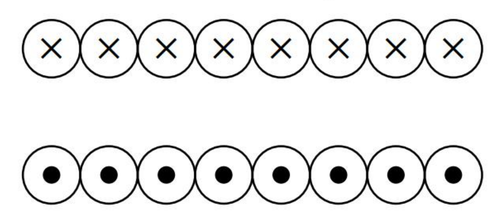
3 **a** A positively charged plate is 5.00 cm above a negatively charged plate, and the electric field strength between the plates is $3.45 \times 10^{2}\,\mathrm{N\,C^{-1}}$. Calculate how much work is done by the electric field to move a proton from the negative to the positive plate.

b An electron travels 3.50 mm in a circular arc around a positive point charge that generates an electric field of $7000\,\mathrm{N\,C^{-1}}$. The electron's path is represented below. State what work is done by the electron in moving along this arc. Explain your answer.



4 **a** Two wire conductors run parallel to each other as shown below. Draw the direction of conventional current through the wires that will result in a force of attraction between them.

b Draw field lines around the solenoid below to represent the direction of the magnetic field that is created when a current flows through the solenoid coil. Label the north and south poles of the solenoid.



5 A motor is constructed by placing a single wire coil in a magnetic field. Consider one part of the coil with length 50 cm running perpendicular to a magnetic field of strength 2 mT.

a Calculate the force that will act on the length of coil when a current of 1.5 A flows through it.

b The length of coil is arranged so that the current runs from north to south in the coil and the magnetic field runs from east to west. State the direction of the force that acts on the length of coil.

6 A drone helicopter with metal rotor blades of length 15 cm from axis to tip is flying in Australia, where the vertical component of Earth's magnetic field is approximately 5×10^{-5} T upwards.

a Calculate the magnetic flux due to Earth's magnetic field that passes through the circular area swept out by the rotor blades.

b Assume the rotor spins at 10 revolutions per second. Calculate the magnitude of the average EMF induced between the axis and the tip of the rotor blade due to its rotation in Earth's magnetic field.

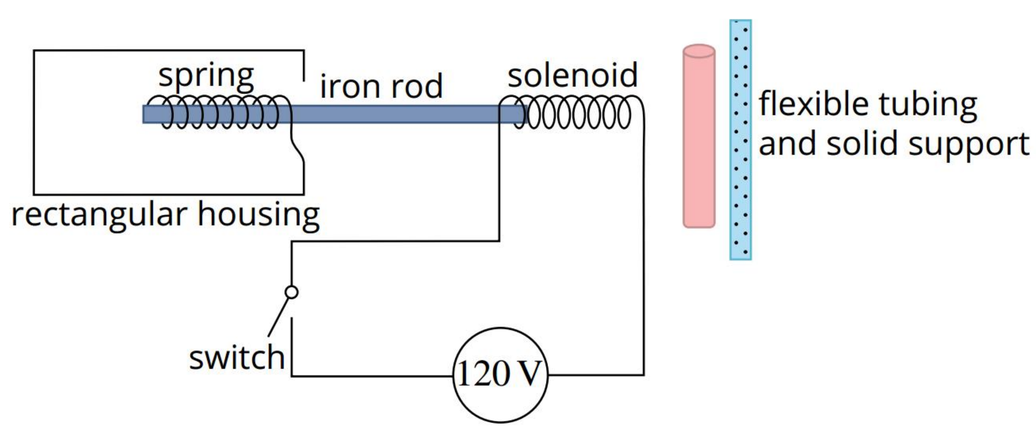
7 A charged Styrofoam™ ball of mass 0.32 g hovers 2.0 cm above a plate carrying a charge of -4.72×10^{-7} C. (The Styrofoam™ ball maintains its position due to a force between itself and the plate below.)

- **a** State the law that can be used to calculate the force exerted between two charged objects.
- **b** Identify whether the charge on the Styrofoam ball is positive or negative.
- **c** Calculate the magnitude of the charge on the ball.
- **d** The ball has developed its charge by accumulating electrons on its surface. Calculate how many electrons it needs to accumulate to gain the charge calculated in part **c**.

8 A model village has 15 electrical components, each rated as 6 V and 0.5 A, connected in series. The model's circuit is connected to the secondary coil of an iron core transformer that has a 1000-turn primary coil. The primary coil is connected to the 240 V, 50 Hz mains supply.

- **a** Calculate the total voltage the circuit will need to supply to operate the 15 components.
- **b** Identify how many turns are in the secondary coil of the transformer.
- **c** Determine the power being supplied by the secondary coil.
- **d** Calculate the power supplied by the primary coil of the transformer assuming the transformer has an efficiency of 85%.

9 A student designs a simple solenoid valve system to control the flow of a liquid through flexible tubing by closing and opening the tubing. It is comprised of an iron rod with a spring coiled around it at one end. One end of the spring is attached at one end of the rod and its other end is attached to a rectangular housing. The tubing is fixed to a solid support. The system is represented by the diagram below.



- **a** Explain how the system will operate to close and open the tubing, using the appropriate physics concepts.
- **b** Identify two ways to increase the force with which the iron rod will push the tubing closed.

10 If the strength of a magnetic field 20.0 cm away from a current-carrying wire is 3.0×10^{-6} T, calculate the current that passes through the wire.

11 A practical investigation was carried out to determine the relationship between the force acting on a current-carrying wire in a magnetic field and the magnitude of the current.

1.2 cm of the wire was placed in a uniform magnetic field between two magnets. The current was varied, and the force on the wire was measured. The following results were obtained.

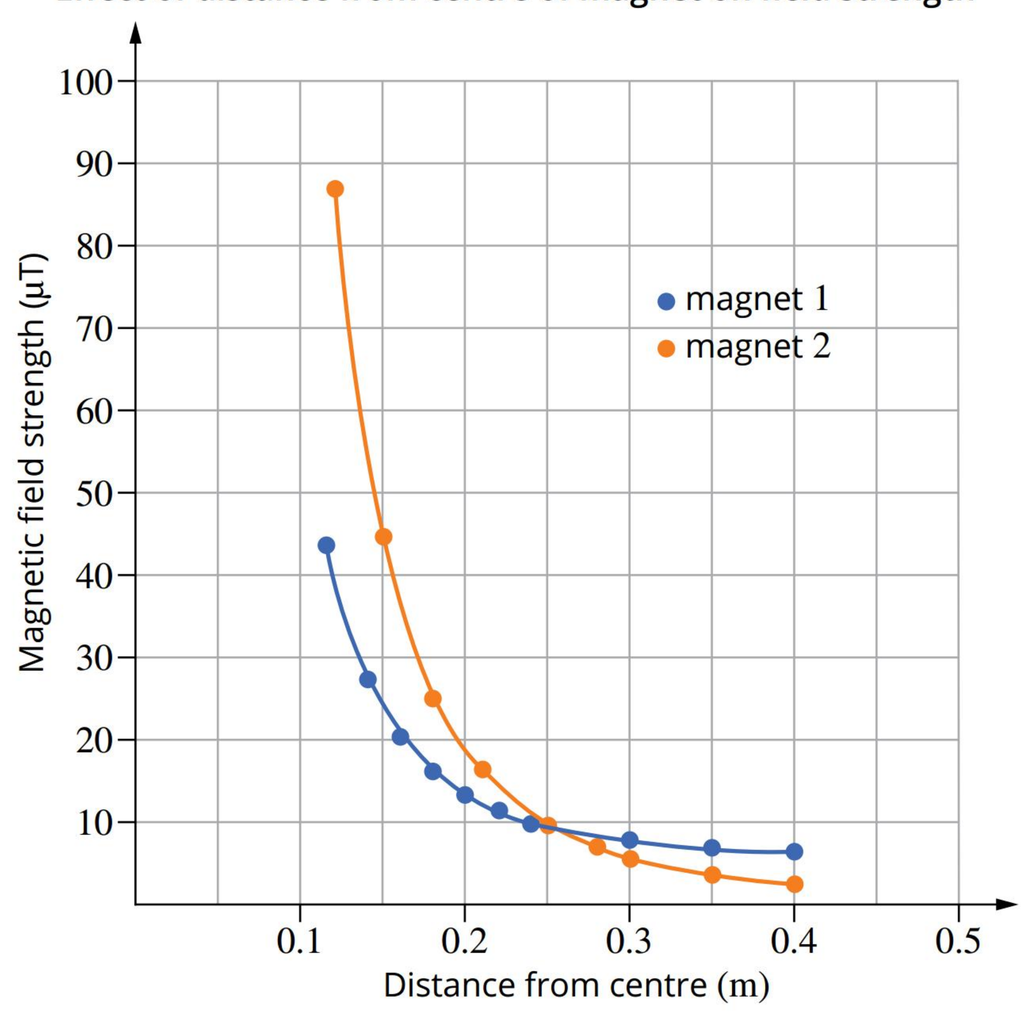
I (A)	*F* (mN)
0.5	1.7
1	3.6
1.5	5.4
2	7.1
2.5	9.8
3	10.8
3.5	12.5

- **a** Create a graph of the results.
- **b** Identify a mathematical relationship between force acting on the wire and the current passing through the wire. Discount the *y*-intercept as negligible.
- **c** Use the graph to determine the strength of the magnetic field between the two magnets used in the experiment.

12 A student wants to compare the strength of bar magnets of different lengths. The magnets will be used in different orientations, so the student decides that all distance measurements will be to the centre of the bar.

Two magnets were measured and the following graph was produced.

Effect of distance from centre of magnet on field strength



a Describe an apparatus and method that could be used to obtain this data.

b Compare the two magnets using the graph above.

c Propose a scenario in which magnet 1 would be preferable to magnet 2.

13 Use the information below to answer the questions that follow.

At its simplest, a mobile telephone works like a radio transmitter and receiver. When you speak into your mobile phone, the sound waves are converted to an electrical signal by a transducer. The electrical signal is called an audio signal because its frequencies are the same as the audible frequencies of sound wave; that is, 20 to 20 000 Hz. The oscillating electrons from the alternating current of the electrical signal travel to the transmitting antenna where they are converted to electromagnetic waves.

The electromagnetic waves from the sender's phone are picked up and relayed by the mobile telephone towers in the network until they reach the receiver's telephone. The antenna in the receiver's phone picks up the electromagnetic waves, which cause the electrons in the receiving antenna to oscillate, creating an electrical signal. This signal is converted back to sound waves heard by the person receiving the telephone call.

a Compare the frequency of oscillations of the electrons in the transmitting antenna to the frequency of the electromagnetic waves sent out by the transmitting antenna.

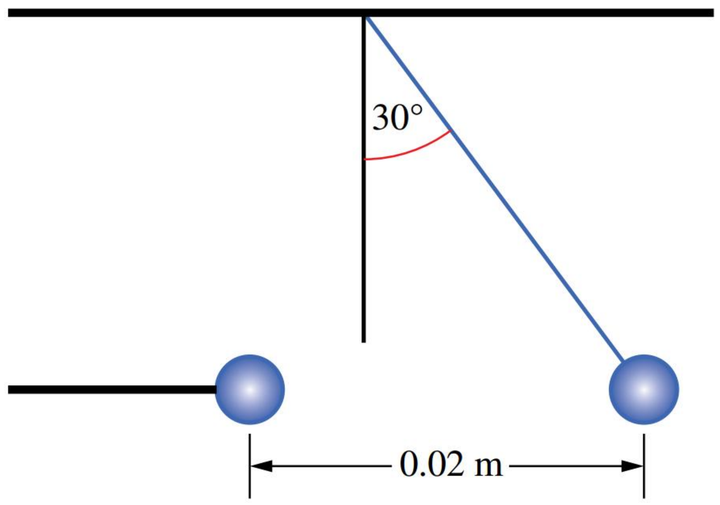
b Calculate the wavelength of an electromagnetic wave resulting from an electrical signal with the maximum audio frequency.

c The electromagnetic wave generated by the audio input in a phone is carried by a carrier wave; that is, the audio wave is superimposed on the carrier wave. For many mobile networks in Australia, the frequency of the carrier wave is in the 850 MHz band.

i Compare the wavelength of the carrier wave with the wavelength of the highest audio frequency. State which has the longer wavelength.

ii Calculate the relative size of the wavelengths of the audio wave and the carrier wave.

14 Pith balls are small, very lightweight balls that retain charge particularly well. They can be used to investigate Coulomb's Law. An experiment was carried out using two pith balls, each with a mass of 1.0 g. Both were charged with an equal amount of charge. One of the pith balls was suspended with an insulating line while the other was brought to within 2.0 cm of the first. The suspended ball was deflected to an angle of 30° from the vertical by the electrostatic force from the other ball. as shown in the following diagram. At an angle of 30°, the suspended ball is in equilibrium.



a Draw a force diagram showing all forces acting on the suspended ball.

b Calculate the charge on each of the pith balls.

15 Two point charges, one with a charge of +q and the other with a charge of +4q are 12 cm apart.

Determine the distance from the charge of +4q where the net electric field strength in a line directly between the two charges would be zero.

16 Rubbing a plastic ruler on the sleeve of a woollen jumper will negatively charge one side of the plastic ruler. Assuming this creates a potential difference of 180 V between the two sides of the ruler:

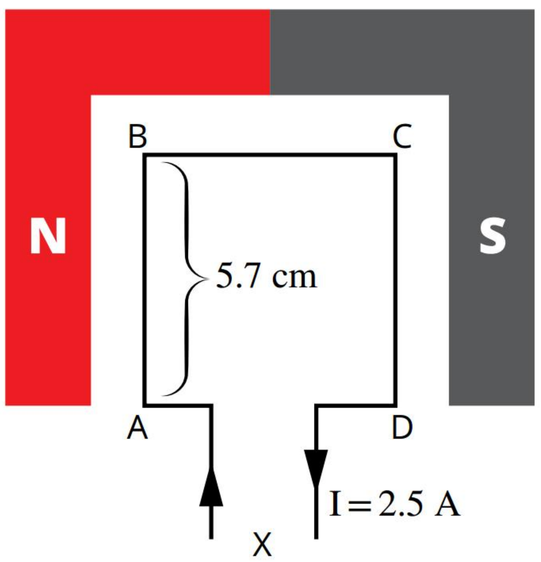
a State whether a positive point charge would have more electrical potential energy on the charged or uncharged side of the ruler.

b Determine the electrical potential energy a charge of −6.0 pC would have on the side of greatest potential energy.

17 A 50 cm solenoid consisting of 1500 turns is connected to 0.75 A of current. Determine the magnitude and direction of the magnetic field inside the solenoid.

18 Calculate the number of turns per meter that will produce a magnetic field strength of 5.1 mT inside a solenoid with a current of 3.0 A.

19 A conducting coil ABCD is placed inside a 1.2 T horseshoe magnet as shown.

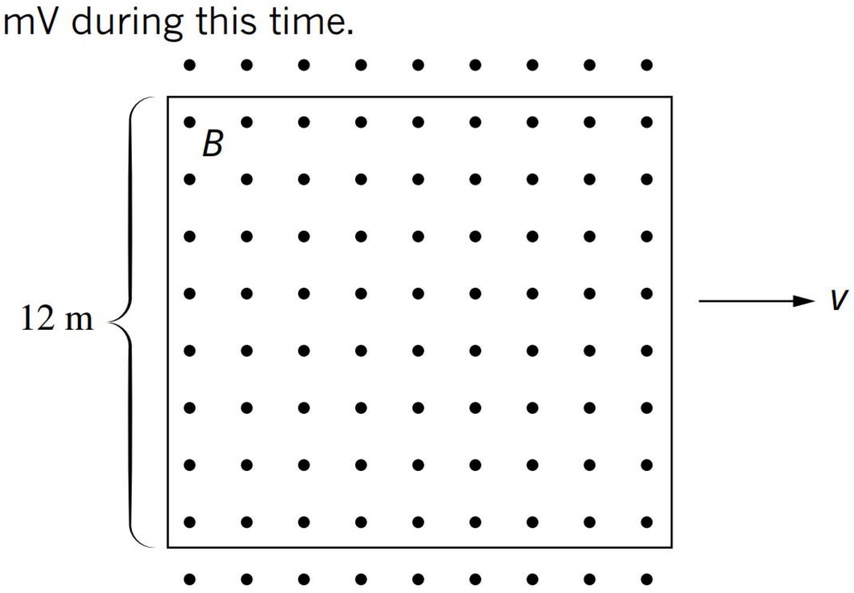


Calculate the magnitude and direction of the force acting on sides AB and CD of the coil. And hence, determine which direction the coil will rotate if viewed from point X.

20 An electron beam is accelerated from rest across a potential of 3.0 kV. It is then subjected to simultaneous electric and magnetic fields perpendicular to its motion. The electrons emerge with no deflection. Calculate the distance between the parallel plates providing the electrical field if the potential difference across the plates is 3.0 kV and the strength of the applied magnetic field is 1.6×10^{-3} T.

21 Assume you were making an electromagnet and wanted to create a strong magnet that uses the least amount of power. Propose the most appropriate method to increase the magnetic strength while using the least amount of power.

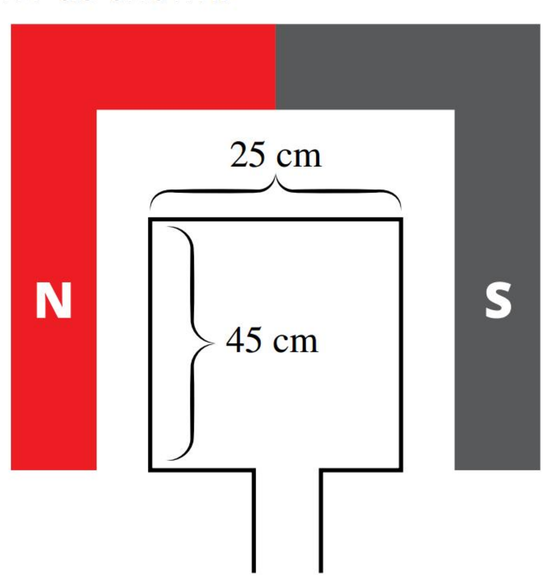
22 A square loop of conducting wire is placed within a magnetic field directed into the page as shown. The loop is moved at a speed of $3\,\text{m s}^{-1}$ so that it is completely out of the magnetic field creating an induced EMF of 3.4 mV during this time.



a Calculate the strength of the magnetic field.

b Comment on how the induced EMF demonstrates conservation of energy.

23 A rectangular loop is placed within a magnetic field of strength 34 mT as shown.



The loop is rotated through an angle of 28° in 32 ms. Calculate the induced EMF in the coil through this time.

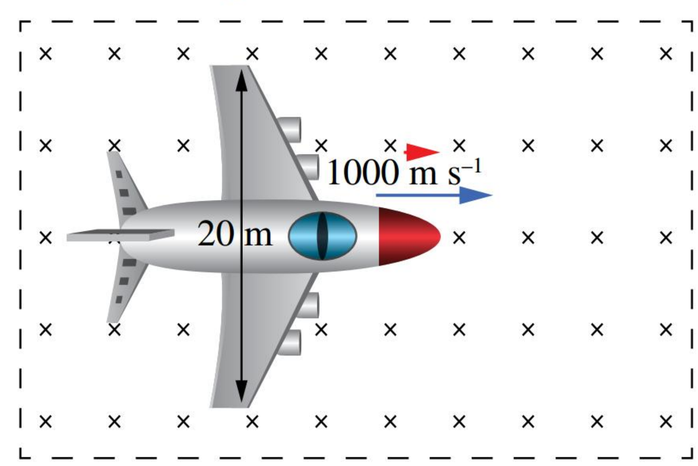
24 An astronaut on their way to Mars is using a handheld radio to communicate with Earth. The radio operates at a frequency of 150 MHz. Describe the nature of these electromagnetic waves and explain how they are produced by the oscillating charges in the radio's antenna.

25 An incandescent lightbulb filament is heated to a high temperature to produce light.

a Explain how heating the material produces an electromagnetic wave.

b Contrast the production of EMR via a lightbulb to that produced in an antenna.

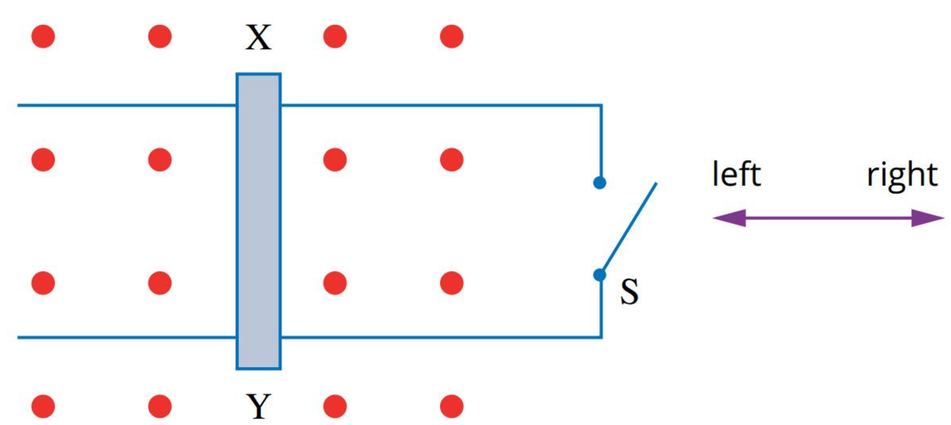
26 The aircraft shown has a wingspan of 20.0 m and is moving at a speed of $1000.0\,\text{m s}^{-1}$ in the magnetic field of Earth in a plane perpendicular to the lines of the field, where the flux density is 2.5×10^{-5} T.



a Calculate the magnitude of the induced EMF between the wingtips of the aircraft.

b Predict how this EMF would change in magnitude if the aircraft was to complete a 90° turn downwards so that it was flying parallel to Earth's magnetic field.

27 A copper rod, XY, of length 20.0 cm is free to move along a set of parallel conducting rails as shown in the following diagram. These rails are connected to a switch, S, which completes a circuit when it is closed. A uniform magnetic field of strength 10.0 mT, directed out of the page, is established perpendicular to the circuit. S is closed and the rod is moved to the right with a constant speed of $2.0\,\text{m s}^{-1}$.



a Calculate the magnitude of the induced EMF in the rod in mV.

b Determine the direction of the current through the rod caused by the induced EMF.

UNIT 4 Revolutions in modern physics

TOPIC 1 Special relativity

TOPIC 2 Quantum theory

TOPIC 3 The Standard Model

Unit 4 objectives

Students will:

- describe ideas and findings about special relativity, quantum theory and the Standard Model
- apply understanding of special relativity, quantum theory and the Standard Model
- analyse data about special relativity, quantum theory and the Standard Model
- interpret evidence about special relativity, quantum theory and the Standard Model
- evaluate processes, claims and conclusions about special relativity, quantum theory and the Standard Model
- investigate phenomena associated with special relativity, quantum theory and the Standard Model.

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CHAPTER 08

Special relativity

Galileo and Newton laid the foundations of the 'clockwork universe', a mechanical picture of the world that has underpinned most modern world views. Einstein, along with others such as Bohr and Heisenberg, presented a much richer and more mysterious universe, one that challenges people to think beyond the mechanical picture they so often take for granted.

In this chapter, you will explore the concepts of classical physics, as described by Galileo and Newton, and the evidence that pointed towards the need for some different thinking. Einstein's postulates of special relativity are presented as a solution to the problem of classical physics at speeds approaching the speed of light.

Syllabus subject matter

Topic 1 • Special relativity

SPECIAL RELATIVITY

- Describe observations of natural phenomena that cannot be explained by classical physics, e.g. the presence of muons in the atmosphere and the momentum of high speed particles in particle accelerators. **8.1, 8.2, 8.3, 8.4**
- Describe the concepts of frame of reference and inertial frame of reference. **8.1**
- State the two postulates of special relativity. **8.2**
- Explain how motion can only be measured relative to an observer. **8.1**
- Explain the concept of simultaneity. **8.2, 8.5**
- Describe the consequences of the constant speed of light in a vacuum, e.g. time dilation and length contraction. **8.3, 8.4**
- Describe the concepts of time dilation, proper time interval, relativistic time interval, length contraction, proper length, relativistic length, rest mass and relativistic momentum. **8.3, 8.4, 8.5**
- Describe the phenomena of time dilation and length contraction, including examples of experimental evidence of the phenomena. **8.3, 8.4**
- State the mass–energy equivalence relationship. **8.5**
- Solve problems involving time dilations, length contraction and relativistic momentum using $t = \frac{t_0}{\sqrt{\left(1-\frac{v^2}{c^2}\right)}}$, $L = L_0\sqrt{\left(1-\frac{v^2}{c^2}\right)}$, $p_v = \frac{m_0 v}{\sqrt{\left(1-\frac{v^2}{c^2}\right)}}$ and $\Delta E = \Delta mc^2$.

  8.3, 8.4, 8.5
- Explain the implications of relativistic momentum of objects increasing as they approach the speed of light. **8.5**
- Explain paradoxical scenarios that may arise as a result of special relativity including the twins' paradox, flashlights on a train, and the ladder in the barn paradox. **8.6**

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8.1 Frames of reference

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- explain the Galilean principle of relativity and the principle behind Newtonian mechanics, including an explanation of the link to Einstein's theory of special relativity
- identify two statements about time and space that Newton assumed to be evident and true
- distinguish between an inertial frame of reference and a non-inertial frame of reference
- describe the aether
- explain why scientists believed the aether to exist.

FIGURE 8.1.1 Albert Einstein statue in Washington, D.C., USA

Galileo and Newton developed theories of motion. These theories allowed the relative motion of low-speed objects to be modelled mathematically. This section presents the observations that challenged **classical physics**, and explains the key principles that led to the new physics described by Albert Einstein (Figure 8.1.1) known as the theory of special relativity.

GALILEAN RELATIVITY AND NEWTONIAN MECHANICS

Galileo was particularly interested in relative motion. One of his famous experiments involved the dropping of a cannon ball from the top of the mast of a moving ship. Galileo found that the motion of the cannon ball did not appear to be affected by the motion of the ship: the cannon ball landed next to the base of the mast. His principle of relativity was that you cannot tell if you are moving or not without looking outside of your own **frame of reference.**

Based on the work of Galileo, Isaac Newton established detailed models for the motion of objects such as planets, moons and comets, even falling oranges. According to his equations, the velocity of objects can be calculated relative to any frame of reference, as long as the velocity of the frame of reference is known. The Newtonian principle states that the velocities of objects and frames of reference can be added together to determine the velocity of the object in another frame of reference. This theory is common throughout all his equations and laws.

Consider an object moving in frame of reference A. This frame of reference is moving in another frame of reference, B. The velocity of the object in B is given by:

$$v_{\text{object in B}} = v_{\text{object in A}} + v_{\text{A in B}}$$

A practical example of this could be when a person runs forwards on a train. Here, the train is frame of reference A and the track along which the train moves is frame B. Imagine that the person runs at $5\,\text{m}\,\text{s}^{-1}$ forwards while the train travels at a velocity of $20\,\text{m}\,\text{s}^{-1}$ forwards. The velocity of the person relative to B, the track, is:

$$\begin{aligned} v_{\text{person on track}} &= v_{\text{person in train}} + v_{\text{train on track}} \\ &= 5.0 + 20.0 \\ &= 25\,\text{m}\,\text{s}^{-1} \end{aligned}$$

That is, the person is moving with a velocity of $25\,\text{m}\,\text{s}^{-1}$ forwards when measured in reference to the track.

> A frame of reference is the physicist's way of describing a particular system of measurement coordinates. Your usual frame of reference is Earth's surface, but this does not have to be the case. As long as you make your measurements from a frame of reference that is moving at constant velocity or zero velocity, any measurements of changes of velocity will agree with those made by observers in other steadily moving frames of reference.

In 1687, Isaac Newton published his famous *Principia*. At the start of this incredible work, which was the basis for all physics in the following two centuries and beyond, he notes the following assumptions, which he took as evident and true:

- Absolute, true and mathematical time, of itself, and from its own nature, flows equably without relation to anything external.
- Absolute space, in its own nature, without relation to anything external, remains always similar and immovable.

Newton based all his laws on these two assumptions: that space and time are constant, uniform and straight. So, according to Newton, space is like a big set of *xyz* axes that always have the same scale, and in which distances can be calculated exactly by Pythagoras' theorem. You expect a metre ruler to be the same length whether it is held vertically or horizontally, north–south or east–west, in your classroom or in the International Space Station.

In this space, time flows at a constant rate, which is the same everywhere. One second in Perth is the same as one second in Brisbane, and one second on the ground is the same as one second up in the air or in deep space.

INERTIAL FRAME OF REFERENCE

Einstein was a typical theoretician: the only significant experiments he ever did were thought experiments, or *Gedanken* experiments, as they are called in German.

Many of Einstein's thought experiments involved situations that involved two frames of reference moving with a steady relative velocity. For example, a person stationary in a moving car could be the first frame of reference, and an observer on the road watching that 'stationary' person moving at speed could be the second frame of reference. Newton had referred to these as **inertial frames of reference**, as the law of inertia applied within them (refer to *Pearson Physics Queensland Units 1 & 2, Chapter 7*).

An inertial frame of reference is one that is not accelerating. For example, in an aircraft moving at constant velocity, the passengers will feel they are stationary and are therefore in an inertial frame of reference. When a body does not seem to be acting in accordance with inertia, it is in a **non-inertial frame of reference**, i.e. is accelerating. Consider the same aircraft starting to descend for landing. It will undergo deceleration. This means the passengers are now in a non-inertial frame of reference and will feel a slight 'force' forwards that appears, to them, to come from nowhere.

EINSTEIN AND GALILEAN RELATIVITY

Einstein decided that the elegance of the principle of Galilean relativity was such that it simply had to be true. However, nature did not appear to have a special frame of reference, and Einstein could see no reason to believe that there was one waiting to be discovered. In other words, there is no such thing as an absolute velocity. It is not possible to have a velocity relative to space itself, only to other objects within space. So, the velocity of any object can always be stated as relative to some other object. In the case of the person running on the train at $5\,\mathrm{m\,s^{-1}}$ while the train travels at a speed of $20\,\mathrm{m\,s^{-1}}$, the velocity of the runner can be stated as either $5\,\mathrm{m\,s^{-1}}$ relative to the train or $25\,\mathrm{m\,s^{-1}}$ relative to the track.

Einstein expanded the Galilean principle to state that all inertial frames of reference must be equally valid, and that the laws of physics must apply equally in any frame of reference that is moving at a constant velocity. So, there is no physics experiment you can do, that is entirely within a frame of reference, that will tell you whether or not you are moving. In other words, as you speed along in your train with the blinds down, you cannot measure your speed. You can tell if you are accelerating easily enough: you just hang a pendulum from the ceiling, as seen in Figure 8.1.2c and d. However, the pendulum will hang straight down whether you are travelling steadily at $100\,\mathrm{km\,h^{-1}}$ or are stopped at the station. Consider Figure 8.1.2a and b. There is no way of telling which of the trains is stationary relative to the ground, or which is moving at a constant velocity.

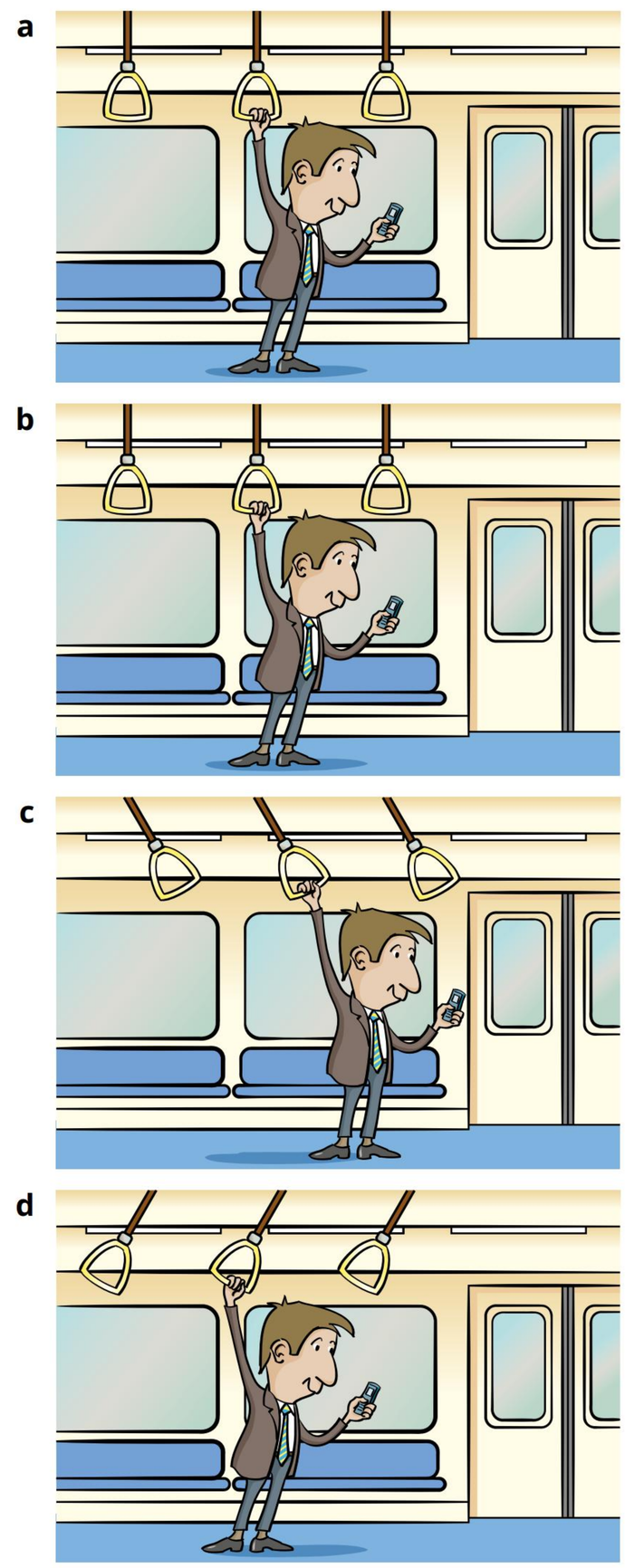


FIGURE 8.1.2 There is no observation or experiment that shows the difference between two inertial frames of reference (a) and (b). In one of the situations illustrated, the train is stationary, and in the other it is moving smoothly at $100\,\mathrm{km\,h^{-1}}$. There is no observation that will tell which one is which. In (c) and (d), the motion of the handles hanging from the ceiling of the train indicate that these trains are not moving at a constant speed.

Einstein's fascination with the nature of light had led him to a deep understanding of Maxwell's work on the electromagnetic nature of light waves. He was convinced of the elegance of Maxwell's equations and their prediction of a constant speed of light. Most physicists believed that the constant speed predicted by Maxwell's equations referred to the speed of light relative to a **medium** (a substance it travelled through). It was thought that the predicted speed would be the speed in the medium in which light travelled, and the measured speed would have to be adjusted for one's own speed through that medium.

As light travelled through the vacuum of space between the Sun and Earth, clearly the medium was no ordinary material. Physicists gave it the name **aether**, as it was an 'ethereal' substance. It was thought, following Maxwell's work, that the aether must be some sort of massless, rigid medium that 'carried' electric and magnetic fields.

This was a real problem for Einstein. If light was emitted from an object that was travelling at a speed through the aether, then the total speed of light relative to the aether would be greater than the fixed speed of light in the aether, according to the principle of Galilean relativity.

8.1 Review

SUMMARY

- A frame of reference is the coordinate system or viewpoint from which someone observes and measures motion.
- Galileo's principle of relativity was that you cannot tell if you are moving or not moving without looking outside of your own frame of reference.
- The Newtonian principle states that the velocities of objects and frames of reference can be added together to determine the velocity of the object in another frame of reference.
- Newton based the laws of motion on two assumptions: that space and time are constant, uniform and straight.
- Newton had referred to two frames of reference moving with a steady relative velocity as inertial frames of reference, as the law of inertia applied within them.
- When a body does not seem to be acting in accordance with inertia, it is in a non-inertial frame of reference or accelerating.
- Einstein expanded the Galilean principle to state that all inertial frames of reference must be equally valid, and that the laws of physics must apply equally in any frame of reference that is moving at a constant velocity.

KEY QUESTIONS

Describe

1 Recall the two assumptions Newton made about space and time when developing his laws of motion.

2 Identify two examples of objects experiencing inertial frames of reference.

3 Identify two examples of objects experiencing non-inertial frames of reference.

4 Describe why the physicists of the late 19th century felt the need to invent the idea of the aether.

Apply

5 Determine the speed at which the sound from a fire truck siren would appear to be travelling in the following situations. The speed of sound in air is $340\,\mathrm{m\,s^{-1}}$.

a You are driving towards the stationary fire truck at $30\,\mathrm{m\,s^{-1}}$.

b You are driving away from the stationary truck at $40\,\mathrm{m\,s^{-1}}$.

6 Determine, from the viewpoint of a stationary observer on a train station platform, the velocity of a passenger running at the same speed as the slow moving train he is in, but in the opposite direction to the train.

8.1 Review *continued*

7 Two spaceships are travelling at a constant relative velocity, then one begins to accelerate. Describe a simple device the passengers in each spaceship could use to determine which ship was accelerating.

8 Explain these two observations using Galileo's principle of relativity.

- **a** A ball thrown straight up in a uniformly moving car comes straight back down.
- **b** A ball thrown straight up in a car that suddenly lands in front of the person who threw it.

9 Determine if the following scenarios are in an inertial frame of reference or not. Justify your reasoning.

- **a** You are seated on a plane. A cup of coffee on the tray table in front of you remains stationary.
- **b** You are inside an elevator moving to a higher floor. You feel heavier than usual.
- **c** A satellite orbits Earth in a circular path at a constant speed.

Analyse

10 A student running at $3.0\,\mathrm{m\,s^{-1}}$ forward releases a javelin thrown horizontally forward at $18.0\,\mathrm{m\,s^{-1}}$ from their frame of reference. Determine the horizontal speed of the javelin from a spectator standing behind the student.

11 Anna is at the front end of a train carriage that is moving at $10.0\,\mathrm{m\,s^{-1}}$. She throws a ball back to Ben, who is 5.0 m away at the other end of the carriage. Ben catches it 0.20 s after it is thrown. Chloe is watching all of this from the side of the track.

- **a** Determine the velocity at which Chloe sees the ball travel.
- **b** Calculate how far, in Chloe's frame of reference, the ball moved while in flight.

12 Imagine that the speed of light has suddenly slowed down to only $50.0\,\mathrm{m\,s^{-1}}$ and this time Anna (still at the front of the 5.0 m train carriage moving at $10.0\,\mathrm{m\,s^{-1}}$) sends a flash of light towards Ben. Consider this information and question **9**, to answer the following:

- **a** Calculate how long it takes the light flash to reach Ben from Anna's point of view.
- **b** Determine how far the light travelled in 0.10 s in Chloe's frame of reference.

13 Max is behind the safety rail holding a ball while watching his little sister go around on a merry-go-round. He sees her following a curved path and throws the ball straight at her, hoping she will catch it. Max's throw misses his sister. Later, his sister wants to know how Max made the ball curve in the air, but Max says he threw it straight. Discuss the reason for their different opinions.

8.2 Simultaneity and the postulates of relativity

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- identify how Einstein resolved the problem of the aether
- explain the Michelson–Morley experiment, including their conclusion
- state the two postulates of special relativity
- recognise the assumptions Einstein had to make for his two postulates to be true
- identify the consequence of accepting the two postulates that goes against classical physics
- describe a simultaneous event
- discuss the statement 'lack of simultaneity' in terms of light.

After Maxwell's discovery that light was nothing more than an electromagnetic wave, the necessity for the existence of the aether was further strengthened, as it was believed that electric and magnetic fields must have a medium in which to travel. As discussed in the previous module, Maxwell's equations predicted that light always travelled at a constant speed regardless of reference frame, which seemed to contradict the idea of an aether medium. The next step for scientists was the detection of the aether, as this would help confirm their understanding of how light waves moved through space.

THE MICHELSON–MORLEY EXPERIMENT

The existence of an aether appeared to be a serious blow for the principle of relativity. It seemed that there may be a frame of reference attached to space itself after all. If this was the case, there was the possibility of an absolute zero velocity.

Scientists needed to test the idea of electromagnetic waves moving through the aether. As Earth is in orbit around the Sun, an aether 'wind' should be blowing past Earth, as Earth moved relative to the aether. This suggested to American physicist Albert Michelson that it should be possible to measure the speed at which Earth was moving through the aether by measuring the small changes in the speed of light as Earth changed its direction of travel. For example, if the light was travelling through the aether in the same direction as Earth, its apparent speed should be slower than usual, at $c - v$, where v is the velocity of Earth. If the light was travelling against Earth's motion, its apparent speed should be faster, as it would be travelling with the 'wind', at $c + v$ (Figure 8.2.1). The differences would be tiny, less than 0.01%, but Michelson was confident that he could measure them.

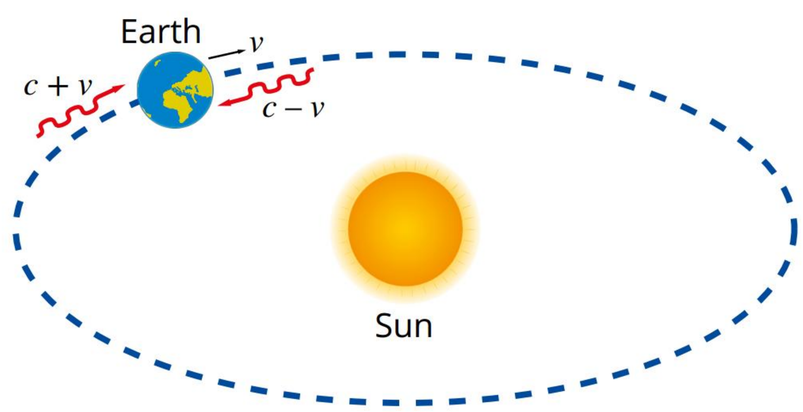


FIGURE 8.2.1 The basic principle of the Michelson–Morley experiment. If the aether is fixed relative to the Sun, and the light is travelling at c relative to the aether and in the same direction as Earth, the apparent speed should be less than c (*that is*, $c - v$). If the light was travelling in the opposite direction to Earth, it should appear faster than c, (*that is*, $c + v$).

In the 1880s, Michelson and his collaborator Edward Morley set up a device known as an interferometer, which could detect changes in the speed of light that might have been due to the aether wind. The interferometer could measure any difference in the time taken for light to travel in two mutually perpendicular directions. Michelson and Morley expected there to be a small difference between the two measurements. However, they found none. Whatever direction Earth was moving in it seemed to be at rest in the aether. Or perhaps there was no aether at all.

While Michelson and Morley's results were consistent with Maxwell's prediction that the speed of light would always appear to be the same for any observer, the apparent absurdity of such a situation led most physicists to believe that some flaw in the theory behind the experiment, or in its implementation, would soon be discovered. Einstein, however, wondered about the consequences of accepting their prediction about the speed of light but at the same time holding on to the principle of Galilean relativity.

THE POSTULATES OF SPECIAL RELATIVITY

Although Einstein accepted both Galileo's and Maxwell's theories despite the apparent contradiction, this still left the question: How could two observers travelling at different speeds see the same light beam travelling at the same speed? The answer, Einstein said, was in the very nature of space and time.

In 1905 he sent a paper to the respected physics journal *Annalen der Physik*. The paper was entitled 'On the electrodynamics of moving bodies'. In this paper he put forward two simple **postulates of special relativity** (statements assumed to be true) and followed them to their logical conclusion. It was this conclusion that was so astounding.

The two postulates of special relativity:

- The laws of physics are the same in all inertial (non-accelerated) frames of reference.
- The speed of light has a constant value for all observers regardless of their motion or the motion of the source.

(The first postulate means that there is no preferred frame of reference and so is sometimes stated as: no law of physics can identify a state of absolute rest.)

The first postulate is basically that of Newton, but Einstein extended it to include the laws of electromagnetism, so elegantly expressed by Maxwell. The second postulate simply takes Maxwell's prediction about the speed of electromagnetic waves in a vacuum at face value.

These two postulates sound simple enough; the only problem was that, according to early classical physics, they were contradictory.

Consider the example illustrated in Figure 8.2.2; Binh is in his spaceship travelling away from Clare at a speed v, and Clare turns on a laser beam to signal Binh. The first postulate seems to imply that the speed of the laser light, as measured by Binh, should be $c - v$, where c is the speed of light in Binh's frame of reference. This is what you would expect if, for example, you were to measure the speed of sound as you travel away from its source: as your velocity gets closer to the speed of sound, the slower the sound waves appear to be travelling.

The second postulate, however, tells you that when Binh measures the speed of Clare's laser light, he will find it to be c, that is, $3 \times 10^8\,\mathrm{m\,s^{-1}}$. So, at first glance, these two postulates appear to be mutually exclusive. To resolve this problem, Einstein went back to the two assumptions on which Newton had based his theories:

- Absolute, true and mathematical time flows equably without relation to anything external.
- Absolute space, without relation to anything external, always remains similar and immovable.

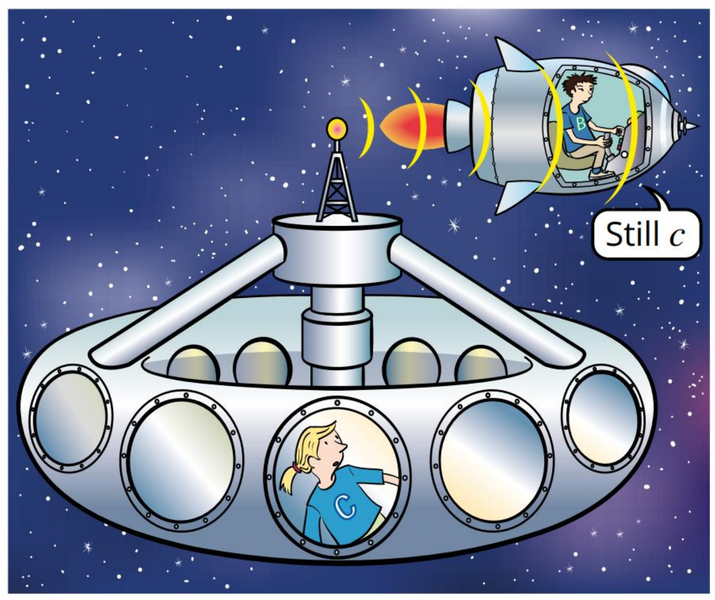


FIGURE 8.2.2 The two postulates of special relativity are seemingly contradictory. His first postulate indicates that the speed of the laser light, as measured by Binh, should be $c - v$, whereas his second postulate indicates it should be c. Einstein revisited Newton's assumptions to resolve this problem.

Newton based all his laws on the assumptions that space and time are constant, uniform and straight. Einstein realised that these assumptions might not be valid, at least not on scales involving huge distances and speeds approaching the speed of light. The only way in which the two postulates of special relativity can both be true is if both space and time are not fixed and unchangeable.

FLASHING LIGHTS IN A TRAIN

To illustrate the consequences of accepting the two postulates he put forward, Einstein discussed a simple thought experiment. It involves a train moving at a constant velocity.

Amaya and Binh have boarded the train and Clare is outside the train. This train has a flashing light bulb set right in the centre of the carriage. The train has an amazingly powerful engine and can move across the tracks at nearly the speed of light. In their inertial frame of reference, Amaya and Binh are stationary while Clare on the ground outside is moving past them at high speed (Figure 8.2.3).

Amaya and Binh stand in the centre of the train and watch the flashes of light as they reach the front and back walls of the carriage. They find that the flashes reach the front and back walls at the same time. Outside, Clare is watching the same flashes of light. Einstein was interested in when Clare saw the flashes reach the end walls.

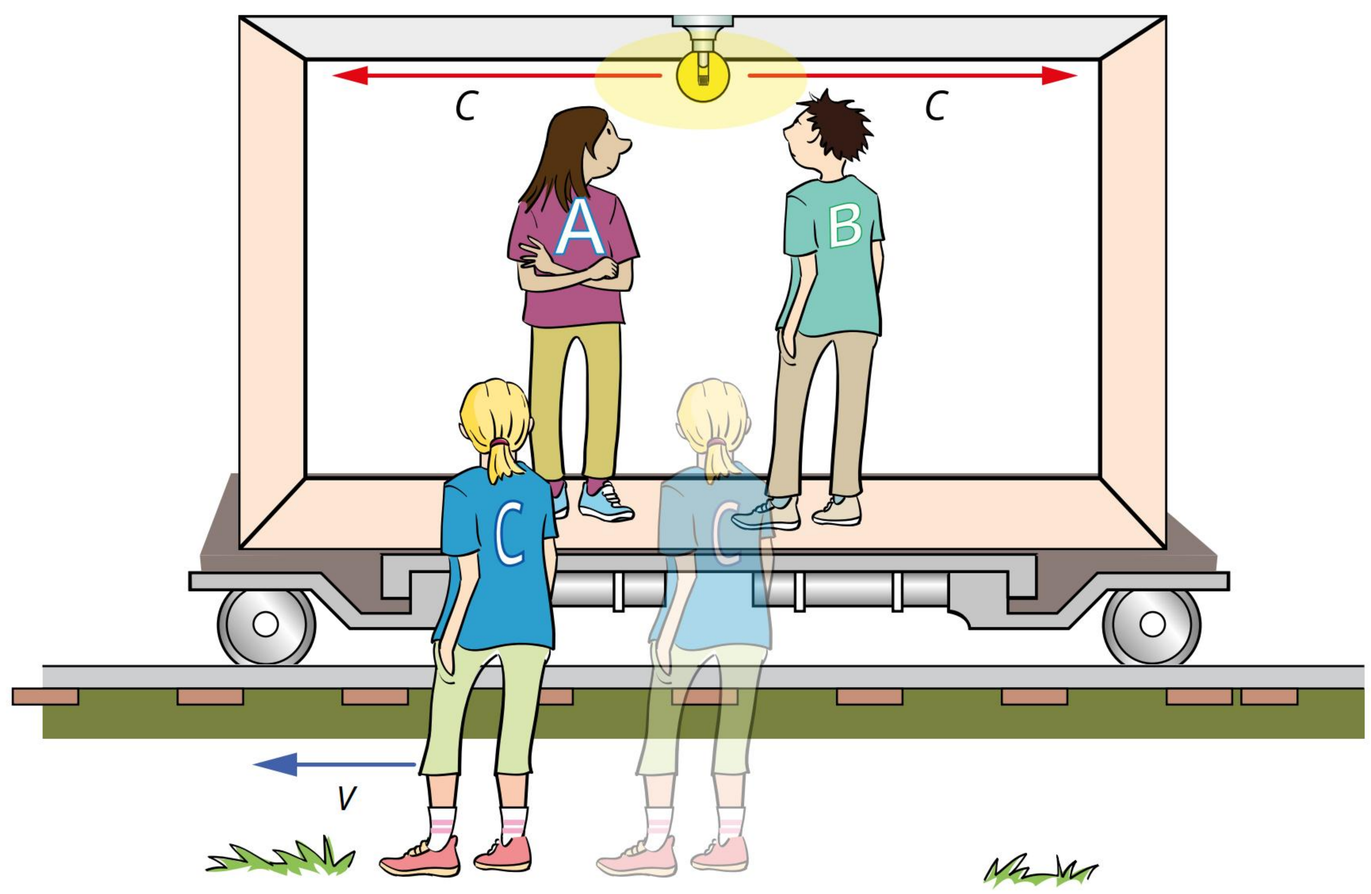


FIGURE 8.2.3 At the centre of the carriage, Amaya and Binh see the light reach the front and the back walls of the train at the same time. Outside, they see Clare moving past the carriage at near the speed of light.

To appreciate Einstein's ideas, you need to contrast them with what you would normally expect. Consider a situation in which Amaya and Binh are rolling balls towards opposite ends of a train carriage. It is important to appreciate that, although Clare, the outside observer, measures the ball's velocity to be different from that measured by Amaya and Binh, the times at which the various events (balls hitting the ends of the carriage) occur must be the same.

If you had discussed a pulse of sound waves travelling from the centre of the train, you would find exactly the same result: Clare always agrees with Amaya and Binh that the time taken for balls, or sound waves, to reach the end walls is the same. But what about something that moves much faster: light?

Einstein's second postulate of special relativity tells you that all observers see light travel at the same speed. Amaya, Binh and Clare will all see the light travelling at $3 \times 10^8\,\mathrm{m\,s^{-1}}$; they do not add or subtract the speed of the train.

In Clare's frame of reference, she is stationary, and it is the carriage containing Amaya, Binh and the flashing light bulb who are moving past her at near the speed of light (Figure 8.2.4). There is a time delay between the bulb flashing and the light reaching the walls and, due to the fast speed of the train, the location of the walls has moved significantly in this time in Clare's frame of reference. The wall in the direction of travel is now much further away from the origin of the flash and continues to travel further away, while the wall opposite the direction of travel is much closer and continues to travel closer. As the speed of light is constant in all inertial frames of reference, Clare will see the light hit the closer wall first as it travels towards the origin of the flash and then the further wall afterwards once the light catches up to it.

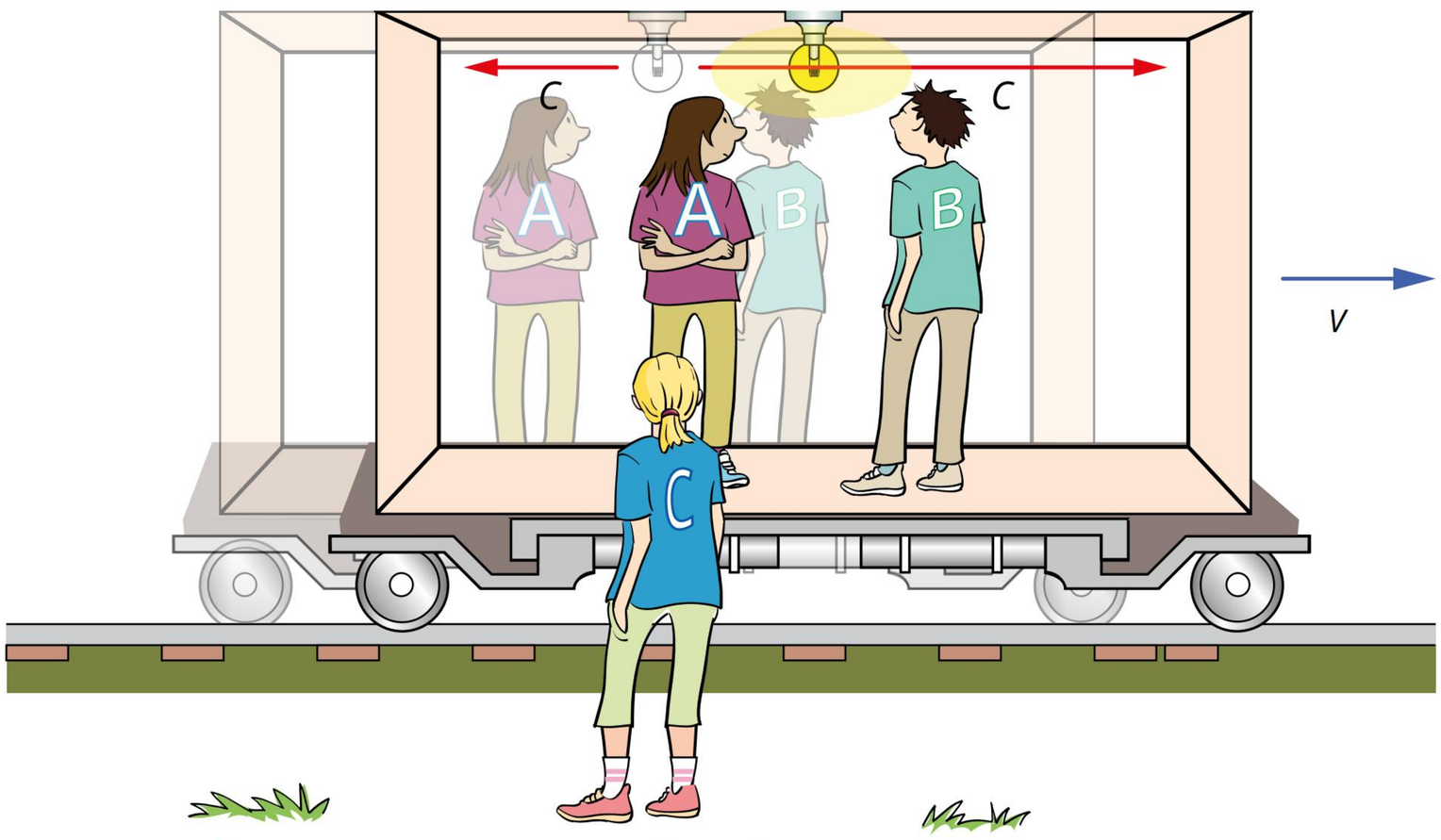


FIGURE 8.2.4 Clare sees the light reach the back wall first, and then the front wall.

This goes against the principles of classical physics. Amaya and Binh saw the light flashes reach the ends of the carriage at the same time; Clare saw them reach the walls at different times.

The idea that two events that are **simultaneous** (occur at the same time) for one set of observers but are not simultaneous for other observers was considered outrageous.

For the postulates of special relativity to be true, two events that might be simultaneous for one observer are not necessarily simultaneous for all observers. This theory has some interesting applications to space travel.

SIMULTANEITY

The big difference between light and balls (and sound), is the strange notion that two sets of observers always see the speed of light as being exactly the same. The velocity of a thrown ball or the velocity of sound in Amaya and Binh's frame of reference will always be different from that in Clare's frame of reference by exactly the velocity of the train. For light, however, there is no difference. As a result, events that are simultaneous for one set of observers might not be simultaneous for others. This is a very strange situation that is referred to as a lack of **simultaneity**.

The people in the train would need extremely precise devices, such as an **atomic clock**, which has the ability to measure time to an incredible number of decimal places and amazingly quick reflexes to take their measurements.

Simultaneity is when two events occur at the same time, or simultaneously. Special relativity can cause a lack of simultaneity, when two events occurring simultaneously in one frame of reference do not occur simultaneously in another frame of reference.

Under normal circumstances, there is no chance of detecting the lack of simultaneity of light beams hitting the front and back walls of a train. This is because the differences in time are about a millionth of a microsecond, well beyond the capacity of even the best stopwatches. The reflexes required to see the light reach the back wall, then see the light encounter the front wall, would also be beyond human ability.

Although Einstein's thought experiments are purely hypothetical, other experiments based on these ideas are well within the capacity of modern experimental physics. In all cases they confirm Einstein's ideas to a high degree of accuracy.

Einstein said that the only reasonable explanation for how two events that were simultaneous to one set of observers were not simultaneous to another is that time itself is behaving strangely. The amount of time that has elapsed in one frame of reference is not the same as that which has elapsed in another.

Einstein's idea was that time and distance are relative. They can have different values when measured by different observers. Simultaneous events in one frame of reference are not necessarily simultaneous when observed from another frame of reference. This is difficult to comprehend at first and will take some time to fully appreciate. Basic understanding of time and distance (and perhaps momentum too) needs adjustment when objects travel at close to the speed of light. A certain observer might see light travelling through a distance d in a time t at a speed c. A different observer might see light travelling through a different distance, d', in a different time, t', but still at the same speed, c.

8.2 Review

SUMMARY

- When Michelson and Morley performed their experiment, they did not detect any change in the speed of light whatsoever, which meant that they did not detect any aether wind.
- The two postulates of special relativity are as follows:
  1. The laws of physics are the same in all inertial (non-accelerated) frames of reference.
  2. The speed of light has a constant value for all observers regardless of their motion or the motion of the source.
- Einstein realised that accepting both of these postulates implied that space and time were not absolute and independent, but were related in some way.
- Einstein put forward a simple experiment to illustrate the consequences of accepting the two postulates, involving a train travelling at near the speed of light, which lead to the idea that two events that are simultaneous for one set of observers may not be simultaneous for another.
- Simultaneous events in one frame of reference are not necessarily simultaneous when observed from another frame of reference.
- Time and space depend on the frame of reference in which they are measured.

KEY QUESTIONS

Describe

1 To resolve the apparent conflict resulting from his two postulates, Einstein rejected some of Newton's assumptions. Identify the consequence of this rejection.

2 Describe how Michelson and Morley planned to collect their data in their experiment to determine whether or not aether existed.

3 State the outcome of the Michelson and Morley experiment, and the conclusion they came to after their data was collected.

4 State the two postulates for special relativity.

Apply

5 Describe a scenario (aside from the examples given inside a train carriage) that demonstrates simultaneity.

6 Imagine that Amaya is at the front end of a train carriage moving forward at $10.0\,\mathrm{m\,s^{-1}}$. She shines a laser towards Binh, who is at the other end of the carriage. Clare is watching all this from the side of the track. Determine the velocity at which the light is travelling as measured by Clare.

7 Describe the consequence of the two postulates with an example other than a train moving at near the speed of light.

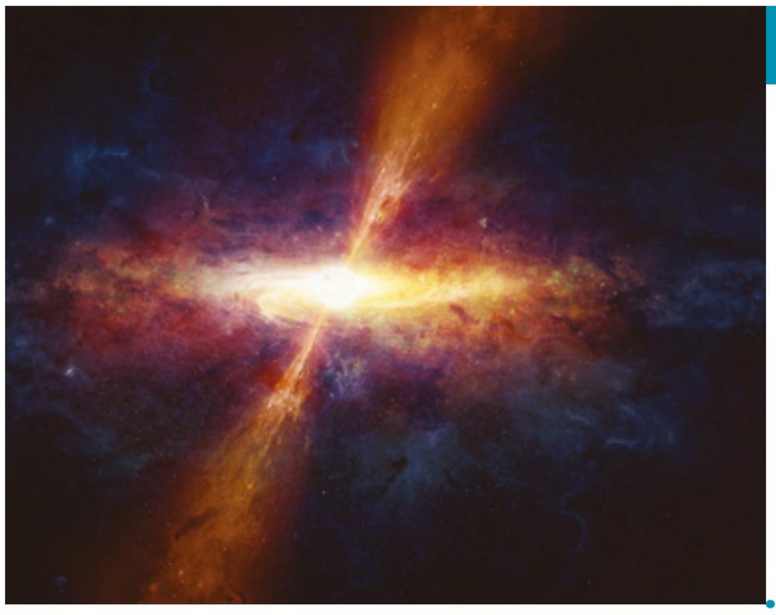
8 Tom, who is in the centre of a train carriage moving at constant velocity, rolls a ball towards the front of the train while at the same time he blows a whistle and shines a laser towards the front of the train. Compare what Jana, who is on the platform outside the train, observes with what Tom observes regarding the speed of the ball, the sound and the light.

Analyse

9 Compare and contrast the postulates of special relativity and classical physics.

10 Barry is standing at an equal distance between two light sources. Each source emits an instantaneous flash. The flashes reach Barry at the same time, so he concludes that the flashes were emitted at the same time. However, Stephen—who is moving towards the left light source—disagrees with this statement. Explain why Stephen disagrees.

8.3 Time dilation



BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- describe time dilation
- explain how a light clock is used to verify time dilation
- describe proper time
- explain what is meant by the terms 'proper time interval' and 'relativistic time interval'
- recall the equation used to calculate relativistic time
- explain how high-altitude muons can reach the surface of Earth using time dilation.

When certain unstable particles such as pions, which have a precisely known decay rate, are accelerated to almost the speed of light, their life spans are measured to be longer than when the particles are stationary. For example, the mean lifetime of the positive pion, π^+, is 0.000 000 026 033 s (26.033 ns) when it is stationary relative to an extremely precise atomic clock that is measuring it. However, when it is moving at 99% of the speed of light, its mean lifetime as measured by the stationary atomic clock is 184.54 ns. This means that the moving pion exists seven times longer than a stationary pion. This section explores the concept of **time dilation** as an explanation for these observations.

TIME IN DIFFERENT FRAMES OF REFERENCE

The consequences of the two postulates of special relativity have been discussed in general terms, when they were applied to thought experiments such as a moving train. Observers inside the train see two simultaneous events while those outside see the same two events occurring at different times. Certainly, the differences are extremely small and would not be noticeable by an observer in any actual train, unless they had an atomic clock. For aircraft flying at supersonic speeds, the differences, although very small, become measurable by the most precise clocks. For subatomic particles, such as pions, created in accelerators like the Australian Synchrotron, the differences in time become more significant, and so in situations like this, where speeds approach the speed of light, it is important to use calculations that take Einstein's theory into account.

The light clock

Consider Amaya and Binh riding in a spaceship that can travel at speeds close to the speed of light. Clare is going to watch from a space station which, according to Clare, is a stationary frame of reference. Amaya and Binh have taken along a clock, which (it is assumed) Clare can read, even from a large distance away.

Like any clock, this clock is governed by a regular oscillation that defines a period of time.

Amaya's clock has a light pulse that bounces back and forth between two mirrors. One mirror is on the floor and the other on the ceiling, as shown in Figure 8.3.1. When a light pulse oscillates from one mirror to the other and back, you can consider that period of time to be 'one unit'. Clare has an identical clock in her own space station, which she can compare to Amaya's clock.

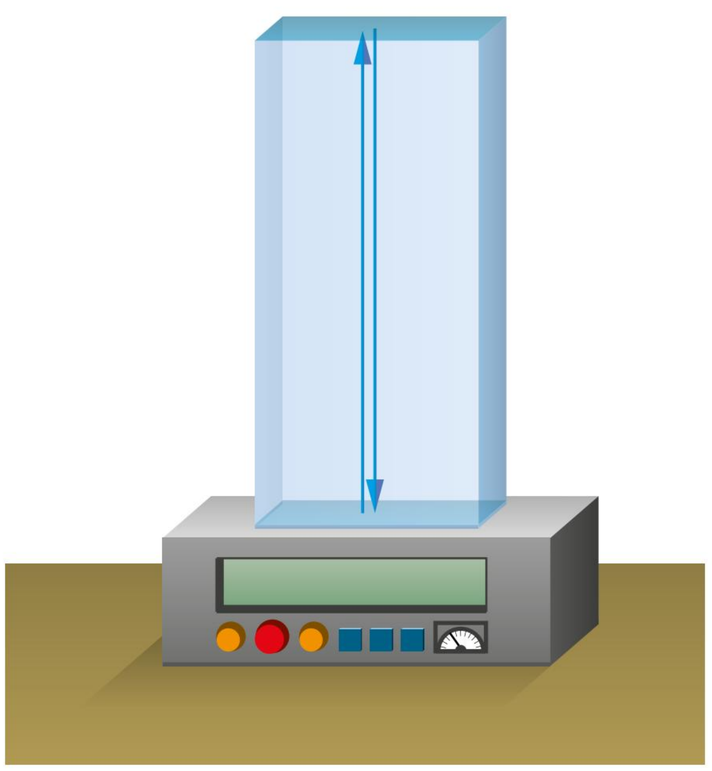


FIGURE 8.3.1 The light clock 'ticks' each time the light pulse reflects off the bottom mirror.

The advantage of this clock is that it can be used to predict how motion will affect the time measured by using Pythagoras' theorem and some algebra. The clock has been set up in the spaceship so that a person in the spaceship sees the light pulses oscillate up and down a distance *d*, that is at right angles to the direction of travel. The distance *d* is shown by a green arrow in Figure 8.3.2. As the spaceship speeds along, an observer outside of the spaceship sees the light trace out a zigzag path, as shown by the red dotted line in Figure 8.3.2.

In their frame of reference, Amaya and Binh see the light pulse travel at the speed of light, *c*, along the distance 2*d*, from the bottom mirror to the top and back again.

Clare sees the light travel a longer path, shown as the red dotted line in Figure 8.3.2.

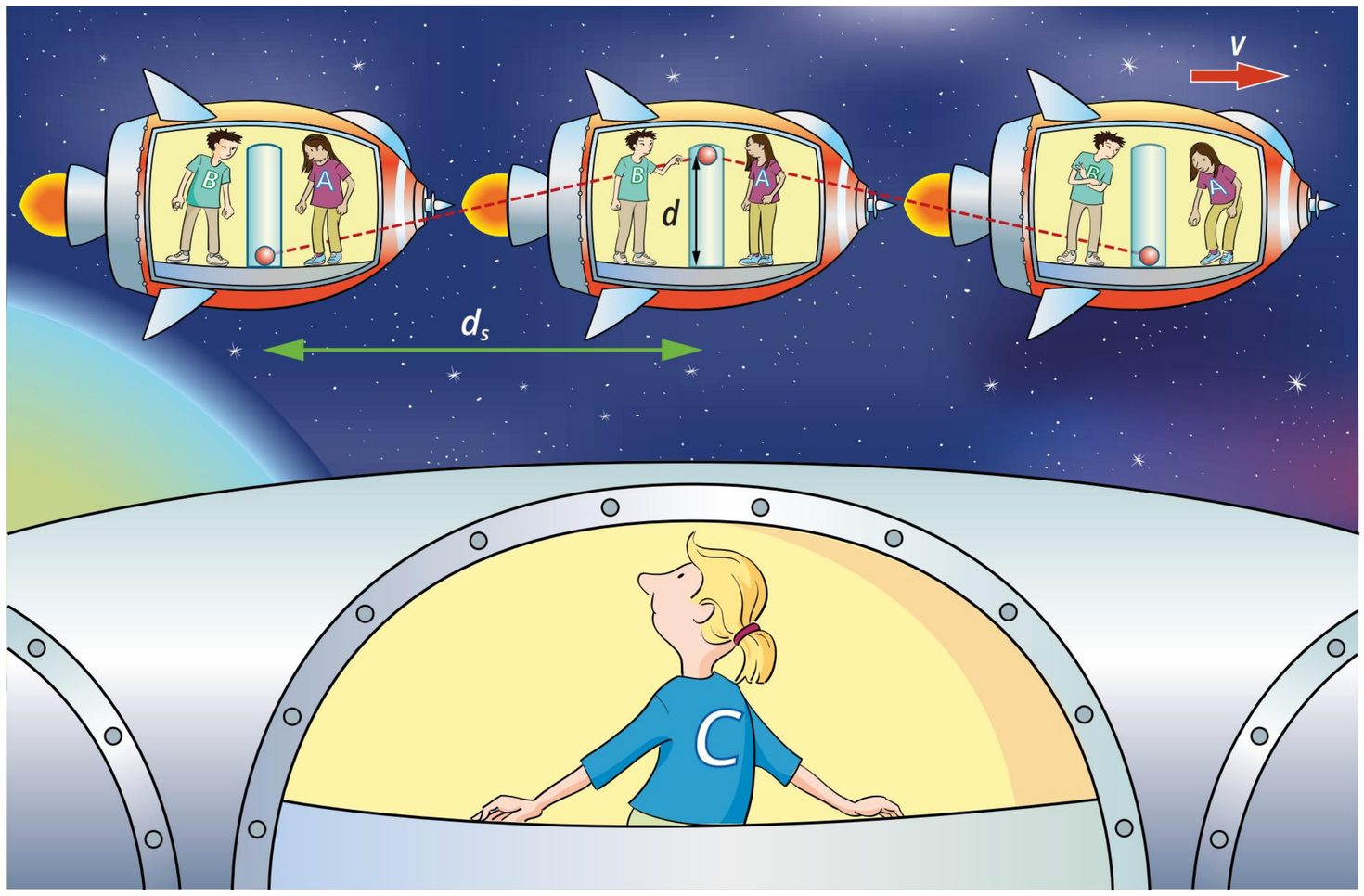


FIGURE 8.3.2 Clare can see that in one unit of time the light clock 'ticks' each time the light pulse reflects off the bottom mirror. She also sees that the light pulses travel a zigzag path between the mirrors.

Relativistic time and proper time

This time measured by Clare, *t*, is greater than the time measured by Amaya and Binh, t_0, for the same event. The symbol *t* is known as the **relativistic time interval**. It is the time that is described only by the theory of relativity and is due to the observer not being in the same frame of reference as the moving clock.

The symbol t_0 is the time that passes on the moving clock according to the clock or a person in the same frame of reference as the clock. This time interval is known as the **proper time interval**. In the example above, the proper time would be Amaya and Binh's unit of time, while the relativistic time is Clare's time as Clare is in a different reference frame.

Relativistic time, *t*, can be calculated by:

$$t = \frac{t_0}{\sqrt{\left(1 - \frac{v^2}{c^2}\right)}}$$

where

t is the relativistic time (s)

t_0 is the proper time (s)

v is the speed of the observed object ($m\,s^{-1}$)

c is the speed of light ($3 \times 10^8\,m\,s^{-1}$)

When the spaceship is travelling at 0.990*c*, a stationary observer such as Clare will measure that a single oscillation of light in the spaceship's light clock will take seven oscillations of her own stationary light clock (Figure 8.3.3). According to Clare, time for the objects and people in the moving frame of reference has slowed down to one-seventh of 'normal' time. This is because as the speed of the moving object gets closer to the speed of light, the relativistic time interval becomes exponentially longer for a stationary observer.

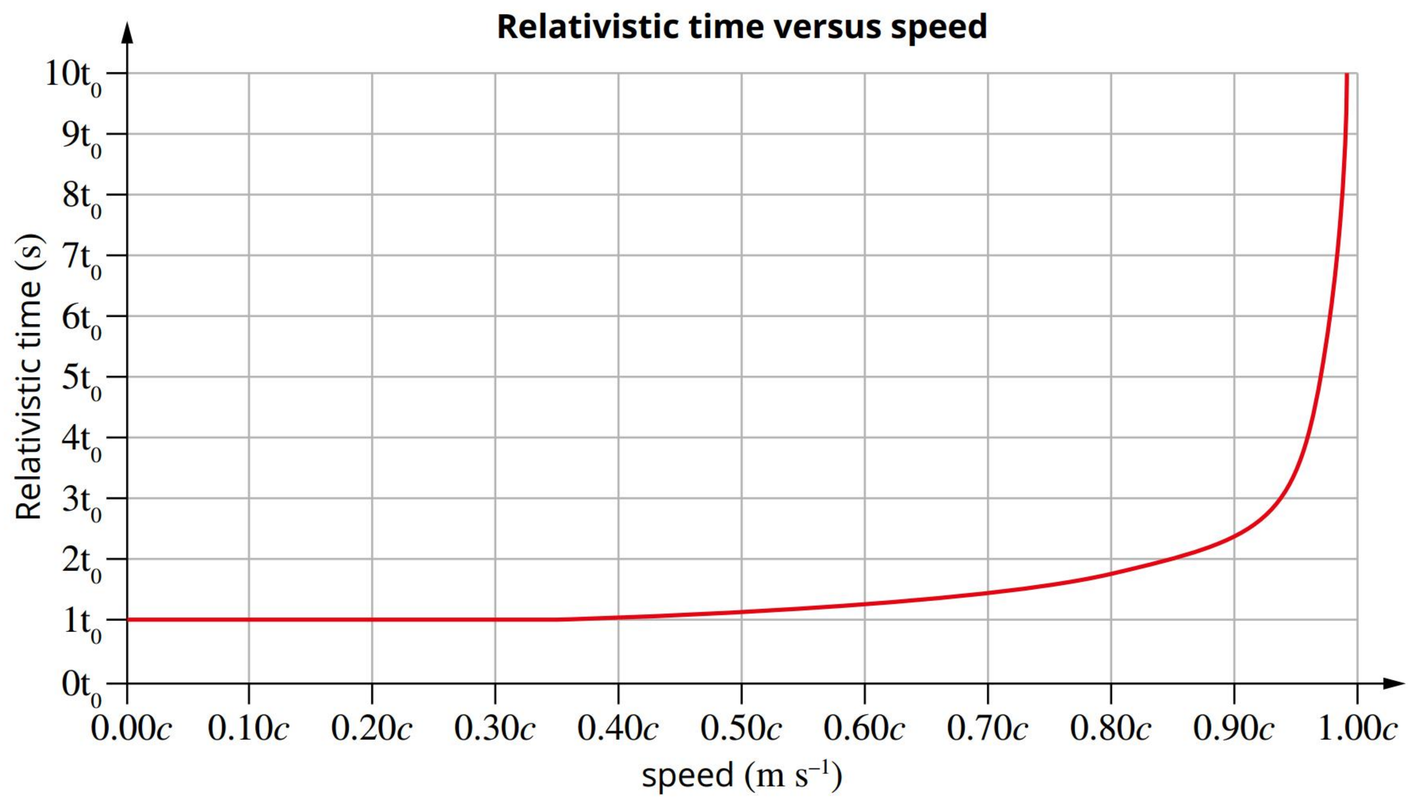


FIGURE 8.3.3 A graph of relativistic time versus speed. As the speed of the moving object approaches the speed of light, a stationary observer will see relativistic time increase exponentially.

As the speed approaches the speed of light, time in the moving frame, as viewed from the stationary frame, slows down more and more. So, if you were able to see the clock travelling on a light wave, the clock would not be 'ticking' at all. In other words, time would be seen to stand still.

It is important to realise that Amaya and Binh do not perceive their time slowing down at all. To them, their clock keeps ticking away at the usual rate and events in their frame of reference take the same time as they normally would. It is the series of events that Clare sees and measures in Amaya and Binh's frame that go slowly. Binh and Amaya are moving in slow motion because, according to Clare's observations, time for them has slowed down (Figure 8.3.4); 'moving clocks run slow'. This is known as time dilation.

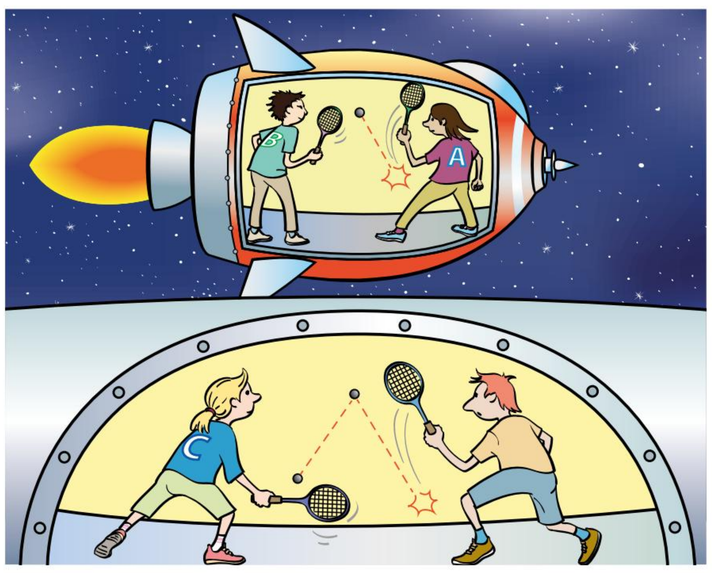


FIGURE 8.3.4 As Clare watches Amaya and Binh play space squash, the ball seems to be moving much more slowly than in her own game.

If Amaya and Binh watch the light clock in Clare's space station, they see that time has slowed down for Clare, as they would observe Clare's moving light clock oscillation taking longer than the oscillation on their stationary light clock. This raises the question: Whose time actually runs slowly?

The answer is that they are both right and symmetrical. The whole point of relativity is that you can only measure quantities relative to some particular frame of reference, not in any absolute sense. Certainly, Amaya and Binh see Clare in slow motion and Clare sees them in slow motion. Remember that there is no absolute frame of reference and so there is no absolute clock ticking away the absolute 'right' time. All that you can be sure of is that time in your own inertial frame of reference is ticking away at a rate of one second per second.

Worked example 8.3.1

TIME DILATION

A stationary observer on Earth sees a very fast car with a passenger passing by, travelling at $2.50 \times 10^8\,\mathrm{m\,s^{-1}}$. In the car is a clock on which the passenger sees 3.00 s pass. Calculate how many seconds pass on another clock held by the stationary observer during this observation.	
Thinking	**Working**
Identify the variables: the time observed by the stationary observer is t, the proper time for the moving clock in its own reference frame is t_0 and the velocity of the car is v.	$t = ?$ $t_0 = 3.00\,\mathrm{s}$ $v = 2.50 \times 10^8\,\mathrm{m\,s^{-1}}$
Identify the formula to calculate relativistic time.	$t = \dfrac{t_0}{\sqrt{\left(1 - \dfrac{v^2}{c^2}\right)}}$
Substitute the values for t_0, v and c into the equation and calculate the answer, t.	$t = \dfrac{3.00}{\sqrt{1 - \dfrac{(2.50 \times 10^8)^2}{(3 \times 10^8)^2}}}$ $= \dfrac{3.00}{0.55277}$ $= 5.43\,\mathrm{s}$

➤ Try yourself 8.3.1

TIME DILATION

A stationary observer on Earth sees a very fast scooter passing by, travelling at $2.98 \times 10^8\,\mathrm{m\,s^{-1}}$. On the wrist of the rider is a watch on which the stationary observer sees 60.0 s pass. Calculate how many seconds pass on the stationary observer's clock during this observation.

EXPLAINING HIGH ALTITUDE MUONS

In Earth's atmosphere, high-energy cosmic rays interact with the nuclei of oxygen atoms 15 km above the surface of Earth to create a cascade of high-velocity subatomic particles. One of these particles is the **muon**, which is unstable. The mean lifetime of a stationary muon, as measured by an atomic clock, is 0.000 002 2 s (2.2 μs). The muons created by cosmic radiation typically travel at 99.9% of the speed of light, so at this speed classical physics would predict that a muon would travel about 660 m:

$$\begin{aligned} s &= v\Delta t \\ &= 0.999 \times 3 \times 10^8 \times 2.2 \times 10^{-6} \\ &\approx 660\,\mathrm{m} \end{aligned}$$

After 10 lifetimes, you can expect there to be essentially no muons remaining. Therefore, after beginning at a height of 15 km and travelling through a distance of 6.6 km, to a height of about 8.4 km above the surface of Earth, you would expect that no muons would be detected.

However, muons created by cosmic radiation are actually detected at Earth's surface. This means that the fast-moving muons have existed for a much longer period of time than they should have. A muon that strikes the surface would have existed at least 22 times its predicted life span as a stationary muon, based on classical physics. Time dilation explains this unusual observation.

The 'normal' mean lifetime (the proper time) of a muon is about 2.2 μs. However, this is the mean lifetime when measured in a stationary frame of reference, that is, in the muon's frame of reference. Muons travel very fast; in fact a speed as great as $0.999c$ is very possible. At this speed, an observer on Earth will see the lifetime of a muon as far greater than 2.2 μs:

$$t = \frac{t_0}{\sqrt{\left(1 - \frac{v^2}{c^2}\right)}}$$

$$= \frac{2.2 \times 10^{-6}}{\sqrt{1 - \frac{(0.999c)^2}{c^2}}}$$

$$= \frac{2.2 \times 10^{-6}}{\sqrt{1 - 0.999^2}}$$

= 49 μs (This is more than 22 times as long as in the stationary frame.)

An observer on Earth would see the muon's time run much slower. The slower time means that many muons live long enough in your frame of reference to reach Earth's surface.

8.3 Review

SUMMARY

- The pulses in a light clock in a moving frame of reference have to travel further when observed from a stationary frame.
- Because of the constancy of the speed of light, this effectively means that time appears to have slowed in a moving frame.
- Proper time interval is the time as measured by an observer who is at rest with respect to a clock or is moving with the clock. In inertial reference frames, it is always the shortest possible time interval.
- Relativistic time interval is the time as measured by an observer who is in motion relative to a clock. In inertial frames of reference, it is always longer than the proper time interval.
- Relativistic time can be calculated using the equation $t = \frac{t_0}{\sqrt{\left(1 - \frac{v^2}{c^2}\right)}}$, where t_0 is the proper time and t is the time within the observers frame of reference.
- Observers in relative motion both see time slowing in the other frame of reference, that is, each sees the other ageing more slowly.
- Time dilation provides the explanation for the occurrence of muons reaching Earth's surface after originating 15 km up in the upper atmosphere, when they should all decay within 7 km of the start of their journey according to classical physics.

KEY QUESTIONS

Describe

1 State the purpose of a light clock.

2 Describe the path of the pulses in a light clock in a moving frame of reference when observed from a stationary frame of reference.

3 Identify whether proper time, t_0, is lesser or greater than relativistic time, t, when observed by an inertial frame of reference.

4 Describe what happens to relativistic time as speed increases.

Apply

5 Explain how muons provide evidence that special relativity is a real phenomenon.

6 Discuss how special relativity affects astronauts traveling at high speeds when observed from Earth.

7 Discuss why two observers in relative motion each see the other's light clock running slower.

8 Einstein once said that a clock at Earth's equator should run slightly slower than one at Earth's poles. Explain why this is not a problem in everyday life.

Analyse

9 Imogen is standing on a train platform as a very fast train passes by at a speed of $1.75 \times 10^8\,\mathrm{m\,s^{-1}}$. She notices the time on a passenger's phone as the passenger drops the phone to the floor. According to the clock on the phone, it takes 1.05 s to hit the floor. Calculate how much time has passed on Imogen's clock during this time.

10 Lin is in a spaceship watching as a satellite approaches at a speed of $2.30 \times 10^8\,\mathrm{m\,s^{-1}}$. On her watch she observes that the solar panels on the satellite unfold in 75.0 s. Determine how much time passes on a clock on the satellite.

11 Calculate how long, in Amira's frame, it would take Ben's clock to tick 1.00 s if Amira saw Ben fly by at 0.500c.

12 A muon created at an altitude of 15.0 km above Earth is moving at a speed of 0.992 times the speed of light. The mean lifetime of a muon at rest is 2.20×10^{-6} s.

- **a** Determine the lifetime of the moving muon as timed by a stationary observer on Earth's surface.
- **b** Calculate the non-relativistic distance and the relativistic distance travelled by the moving muon during one lifetime.

8.4 Length contraction

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- identify that relative motion affects length in the direction of travel
- recall the equation used to calculate length contraction
- explain why the length of an object measured in a moving frame of reference is shorter than that measured by a stationary observer and vice versa
- describe proper length
- explain how high-altitude muons can reach the surface of Earth using length contraction.

The previous module described how time can only be measured relative to some particular frame of reference, and not in any absolute sense. Because of the constancy of the speed of light, this effectively means that time appears to slow down in a moving frame relative to the frame of an observer. Einstein describes how space and time are interrelated, so it follows then that space, and therefore length, is also not absolute.

LENGTH IN DIFFERENT INERTIAL FRAMES

As with time, length depends on who is doing the measuring and the frame of reference in which they make their measurement.

The light clock analysis is appropriate to compare the proper time on the clock in the moving frame of reference (*observed* by Clare in the examples provided in Module 8.3) and the time measured on a clock in the stationary frame (*with* Clare). There was, however, one other condition in this clock analysis—that both Amaya and Clare would agree on the distance, d, between the mirrors.

The clock was deliberately set up in the spaceship so that the light path was perpendicular to the velocity. Distances in the perpendicular direction are unaffected by motion. Indeed, Einstein showed that relative motion affects length only in the direction of travel (Figure 8.4.1).

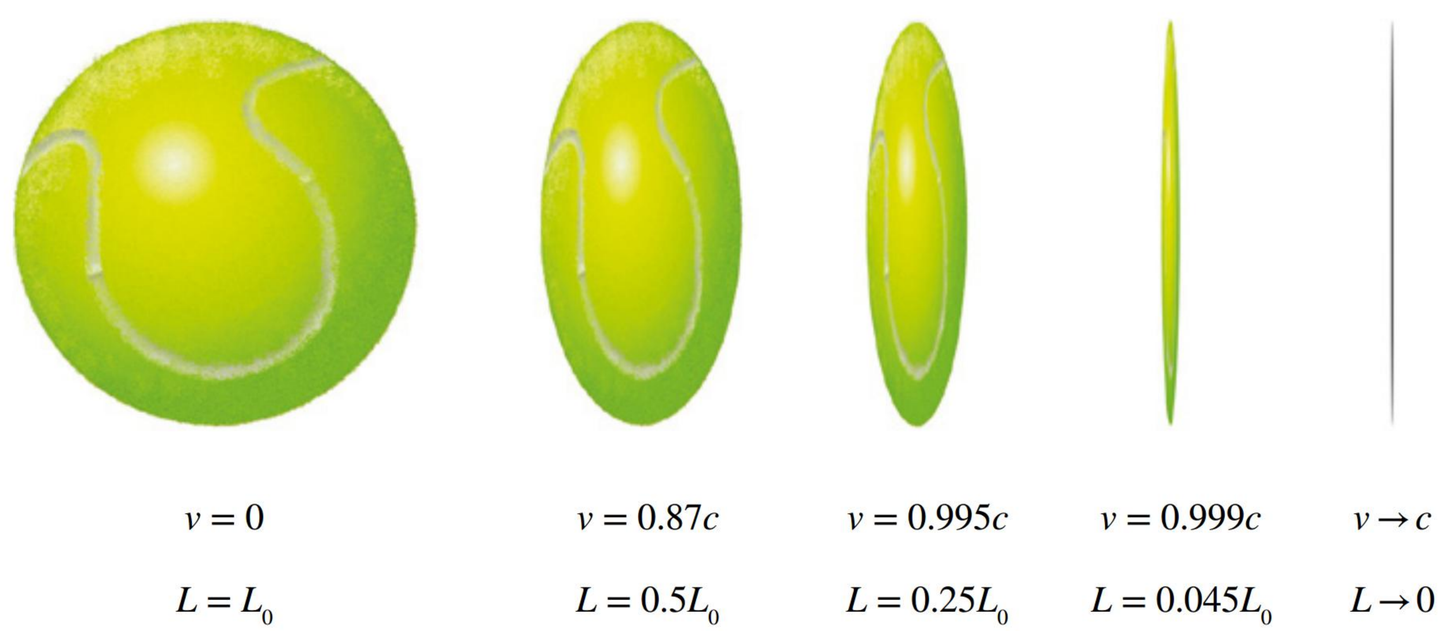


FIGURE 8.4.1 As the tennis ball moves faster to the right, its length in this dimension is contracted, but its height and depth remain the same.

PROPER LENGTH

Recall that proper time is the time between two events that occur at the same point in space. Like proper time, **proper length** is the distance between two points whose positions are measured by an observer at rest with the two points.

If Amaya has a measuring tape which she lays from one end of the carriage to the other, and is at rest with respect to the train, her measurement of the carriage will be the proper length. If Clare lays out a measuring tape along the platform and takes a measurement of the carriage as it travels passed at speed, her measurement of the carriage will be of a contracted length.

On the other hand, Clare measures the length of the platform as the proper length, while Amaya and Binh see the platform as contracted in length.

LENGTH CONTRACTION

Consider the thought experiment in which Clare is standing on a train platform while Amaya and Binh pass by at a speed v. Both Clare and Binh want to measure the length of the train platform on which Clare is standing. Using a measuring tape, Clare measures the length of the platform (which is at rest according to her) as L_0, and says that Binh and Amaya cover this distance in a time equal to:

$$t = \frac{L_0}{v}$$

Using substitution, the formula for length of a moving object as measured from a stationary observer simplifies to:

$$L = L_0\sqrt{1 - \frac{v^2}{c^2}}$$

This is Einstein's **length contraction** equation. This equation shows that an object with a proper length of L_0, will have a shorter length L, *parallel* to the motion of its moving frame of reference when measured by an observer who is in a separate, inertial frame of reference. (L is also known as the **relativistic length,** the length measured in the frame of reference in which the object is in motion.)

Length contraction, L, can be represented as:

$$L = L_0\sqrt{1 - \frac{v^2}{c^2}}$$

where:

L is the relativistic length (m)

L_0 is the proper length (m)

v is the speed of the observed object ($\mathrm{m\,s^{-1}}$)

c is the speed of light ($3 \times 10^8\,\mathrm{m\,s^{-1}}$)

Remember that length contraction occurs only in the direction of travel, not in any perpendicular direction. To Clare, the carriage will appear shortened, but its width and height (the dimensions of the train perpendicular to the direction of travel) will remain unaltered.

Worked example 8.4.1

LENGTH CONTRACTION

Asim, stationary on Earth, sees a very fast car travelling by at $2.50 \times 10^8\,\mathrm{m\,s^{-1}}$. When stationary, the car is 3.00 m long. Calculate the length of the car in the direction of travel as seen by Asim.

Thinking	Working
Identify the variables: the relativistic length measured by Asim is L, the proper length of the car is L_0 and the velocity of the car is v.	$L = ?$ $L_0 = 3.00\,\mathrm{m}$ $v = 2.50 \times 10^8\,\mathrm{m\,s^{-1}}$

Identify the length contraction formula.	$L = L_0\sqrt{1-\frac{v^2}{c^2}}$
Substitute the values for L_0, v and c into the equation and calculate the answer, L.	$L = 3.00 \times \sqrt{1-\frac{(2.50\times10^8)^2}{(3\times10^8)^2}}$ $= 3.00 \times 0.553$ $= 1.66\,\text{m}$

➤ Try yourself 8.4.1

LENGTH CONTRACTION

Annabelle is stationary on Earth and sees a very fast scooter travelling by at $2.98 \times 10^8\,\text{m s}^{-1}$. She measures the scooter's length as 45.0 cm in the direction of travel. Calculate the proper length of the scooter, measured when the scooter is at rest.

DISTANCE TRAVELLED

So far you have been looking at situations in which objects that are in a moving frame of reference are seen as being shorter in the direction of the motion according to an observer who is in a stationary frame of reference. You can also apply length contraction to the distance that a moving object covers as it travels at very high speed.

Recall that no inertial frame of reference is special. Consider Amaya and Binh in their spacecraft travelling to the Moon. According to them, they are stationary and it is space itself that rushes by at high speed. As space zooms by Amaya and Binh, they are travelling a proper distance of 384 400 km from Earth to the Moon. This is the proper length, as it is measured by a device that is in the same frame of reference as Earth and the Moon. As Binh looks out of the window, he measures a much shorter distance to travel.

Length contraction further explains how muons can reach Earth's surface before decaying. Even when travelling at $0.999c$, the half-life of 2.2 μs in the muon's frame of reference means they should decay before travelling 15 km from the upper atmosphere. In the muon's frame of reference, Earth is travelling towards *them* at $0.999c$, and the contracted length from the upper atmosphere is approximately 670 m. Even with their short half-life, most muons can travel this distance and be detected at Earth's surface before decaying.

Worked example 8.4.2

LENGTH CONTRACTION FOR DISTANCE TRAVELLED

Keely pilots a spaceship travelling at $0.997c$ that is travelling from Earth to the Moon. The proper distance from Earth to the Moon is 384 400 km. When Keely looks out of the window, the distance between Earth and the Moon looks much less than that. Calculate the distance that she sees.

Thinking	Working
Identify the length contraction formula.	$L = L_0\sqrt{1-\frac{v^2}{c^2}}$
Substitute the values for L_0 and v into the equation. Cancel c and calculate the answer, L.	$L = 384\,400 \times \sqrt{1-\frac{(0.997c)^2}{c^2}}$ $= 384\,400 \times \sqrt{1-(0.997)^2}$ $= 384\,400 \times 0.0774$ $= 29\,800\,\text{km}$

➤ Try yourself 8.4.2

LENGTH CONTRACTION FOR DISTANCE TRAVELLED

Jin is a stationary observer on Earth who sees a very fast train approaching a tunnel at a speed of 0.986*c*. Jin measures the tunnel's length as 123 m in his reference frame. Calculate the length of the tunnel as seen by the train driver.

Try yourself 8.4.2 leads to an interesting phenomenon. If the proper length of the train is 100 m, then the driver could park the train in the 123 m tunnel with 11.5 m of tunnel extending beyond each end of the train. But when the train is moving at 0.986*c*, then according to the train driver the train will not fit in the tunnel. The driver will observe a proper length of 100 m for the train and a contracted length of 20.5 m for the tunnel. So, there will be approximately 39.7 m of train extending past each end of the tunnel (Figure 8.4.2).

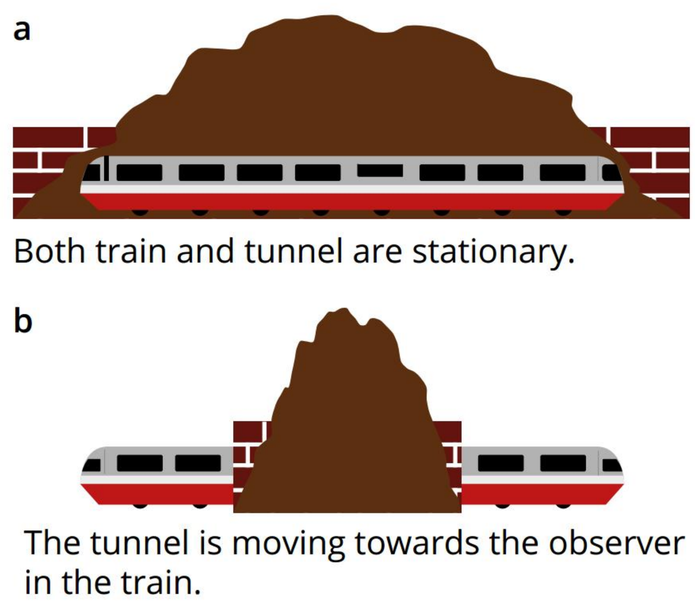


FIGURE 8.4.2 The train both fits in the tunnel and does not fit in the tunnel, depending on your frame of reference.

Similarly, a train (at rest) that is longer than the tunnel will fit completely inside the tunnel if its length is measured by a stationary observer as the train moves past very quickly. In this scenario, the length of the train is contracted to 16.7 m according to the stationary observer (Figure 8.4.3).

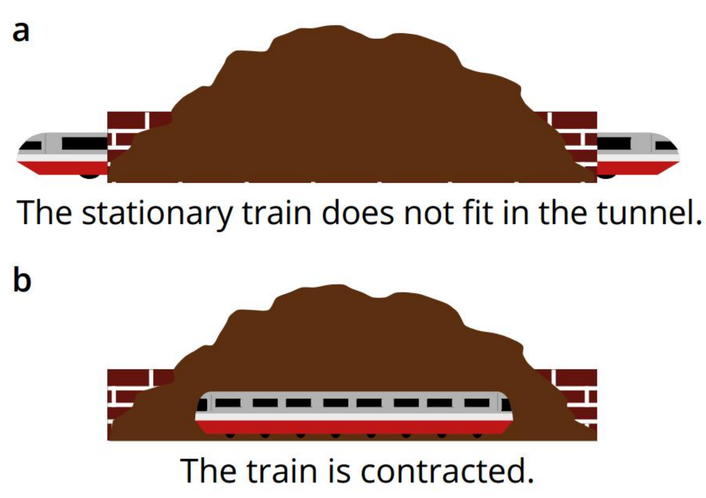


FIGURE 8.4.3 The train both does not fit in the tunnel and does fit in the tunnel, depending on your frame of reference.

8.4 Review

SUMMARY

- The theory of special relativity states that time and space are related. Motion affects space in the direction of travel.
- The proper length, L_0, is the length measured by an observer at rest with respect to the object being measured.
- A moving object will appear shorter, or appear to travel a shorter distance.
- Einstein's length contraction equation is given by: $L = L_0\sqrt{1-\frac{v^2}{c^2}}$, where L_0 is the proper length, L is the relativistic length (contracted length).
- Length contraction supports muons travelling at relativistic speeds being detected at the surface of Earth when they should have decayed according to classical physics.

KEY QUESTIONS

For the following questions let $c = 3 \times 10^8\,\mathrm{m\,s^{-1}}$.

Describe

1 Identify in which direction length contraction occurs.

2 Describe what happens to relativistic length as speed increases.

3 Describe what you would notice about the dimensions of a speeding rocket if you are standing on Earth observing it.

4 Describe the length of an object theoretically travelling at the speed of light from the frame of reference of a stationary observer.

Apply

5 A scientist on Earth measures a spaceship's length as 80 m while the crew measures it as 100 m. Explain why their measurements differ.

6 An observer on a platform measures the length of a train carriage, moving at 0.99*c*, as it passes by. Determine whether the length she has measured is L or L_0. Explain your answer.

7 Sina is standing on a train platform as a very fast train passes by at a speed of $1.75 \times 10^8\,\mathrm{m\,s^{-1}}$. He notices that a passenger is holding a metre rule in line with the direction in which the train is moving. Calculate the length of the metre rule that Sina sees.

8 A jet plane zooms past Cassie at a speed of $660\,\mathrm{m\,s^{-1}}$. Determine the length of the jet as seen by Cassie, who is standing on the ground, if the length of the jet is 23.5 m when parked on the tarmac.

Analyse

9 Emily is standing by the side of the track watching Deng run in an 800 m race in a straight line. Calculate the speed Deng must run for the race to be only 400 m long in his frame of reference.

10 A spaceship travelling at $2.50 \times 10^8\,\mathrm{m\,s^{-1}}$ is measured by a scientist on Earth as having a length of 100 m. Calculate the length of the spaceship in the frame of reference of an astronaut on board.

11 Jordan is in a spaceship speeding at 0.900*c* to the Moon. Jordan is holding a fishing rod that is 2.75 m long, facing in the direction in which the spaceship is moving.

- **a** Determine the length of the rod as observed by an astronaut in the International Space Station, assuming that the space station is at rest with respect to the Moon.
- **b** Calculate the length of the fishing rod as observed by Jordan.

12 Bhavin makes a mistake and builds a garage too short for the owner's car to fit in. The proper length of the garage is 1.50 m and the proper length of the car is 3.50 m. Bhavin suggests that if the owner drives fast enough, Bhavin could stand by the garage and the car would fit.

- **a** Calculate the speed at which the car would need to travel to just fit in the garage when observed by Bhavin.
- **b** Explain why the car owner would not be happy about Bhavin's suggestion by calculating the length of the garage as seen by the driver travelling at Bhavin's suggested speed.

8.5 Relativistic momentum

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- provide an example where relativistic mass can be observed on Earth
- identify the difference between classical momentum and relativistic momentum
- apply the equation used to calculate relativistic momentum
- explain why relativistic momentum further proves that no object can travel at the speed of light
- explain the origin of Einstein's famous equation
- state what is meant by the mass–energy equivalence.

In classical physics and chemistry, the conservation of mass is assumed: applying a force to an object classically does not change its mass and the particles that start out in a chemical reaction are still there at the end. Now it is time to look at the implications of Einstein's relativistic principles on momentum.

MOMENTUM IN PARTICLE ACCELERATORS

Recall from Chapter 3 that, when an object moves in a circular path, it does so as a result of a centripetal force that acts towards the centre of the circular path. Centripetal force therefore acts continuously at a right angle to the velocity of the object. There are several actions that could cause a centripetal force on an object, such as the tension in a string tied to a rubber stopper or the gravitational force of Earth on the Moon.

Another action that causes circular motion is the force on a charged particle that is moving at right angles to a magnetic field. Recall from Chapter 6 that the equation that represents the relationship between the magnetic force (F_B) and the centripetal force (F_c) is:

$$F_B = F_c$$

$$qvB = \frac{mv^2}{r}$$

$$r = \frac{mv}{qB}$$

$$= \frac{m}{qB} \times v$$

The final relationship shows that if the mass m, charge q and magnetic field B are all constant, then the velocity of the charged particle and the radius of its circular path increase at the same rate. However, this is not the case.

In circular accelerating devices such as cyclotrons and the Australian Synchrotron (Figure 8.5.1), it is evident that as the velocity of a charged particle increases, the radius of its path also increases, but to a much greater degree than that expected. In fact, for an electron travelling at 99.999 999% of the speed of light, the radius of the circular path behaves as if an electron has 7000 times the mass of an electron at rest. There is no explanation for this phenomenon in classical physics.

FIGURE 8.5.1 The Australian Synchrotron is a particle accelerator located in Clayton, Victoria. Electrons are accelerated at near the speed of light to produce high frequency synchrotron radiation, which is used for a range of research purposes.

This phenomenon suggests that there is a relationship between mass and energy, which will be discussed later in this module. The increase in kinetic energy required to accelerate objects as they approach the speed of light far exceeded the values predicted by classical physics.

The closer the speed of the object is to the speed of light, the greater the increase in its momentum. This means that an electron in a particle accelerator approaching the speed of light would require an infinitely strong force acting on it, that is, if momentum is very large, then even for a small acceleration, the force acting must be very large. While it is possible for electrons that are accelerating through a particle accelerator to achieve significantly greater momentum than predicted by classical physics, the increase in momentum required at nearly the speed of light reinforces the idea that it is not possible for the electrons to reach the speed of light.

The term **rest mass** is used to describe the mass of an object measured at rest relative to the observer. It is important to remember the rest mass of the object does not change, even though the increase in momentum is greater than the increase in velocity at relativistic speeds (as if the object has a greater mass at relativistic speeds). An electron at rest and an electron in a particle accelerator travelling at 99.999 999% of the speed of light will both have a rest mass of 9.109×10^{-31} kg.

One of, if not the, most famous equations in science arose because of the special theory of relativity. Einstein proposed that a comparatively small amount of matter is equivalent to an enormous amount of energy. This section will examine how he developed his famous equation.

CLASSICAL AND RELATIVISTIC MOMENTUM

Recall that the momentum of an object relates to both its mass and its speed. The more momentum an object has, the more momentum it has to lose before it stops. Recall from *Pearson Physics Queensland Units 1 & 2* that the equation for momentum is $p = mv$, where m is the mass of the object and v is the velocity of the object.

As discussed, when the speed of an object approaches the speed of light, its momentum does not behave according to the equations defined using classical physics. Consider a rocket ship like the one in Figure 8.5.2 travelling at $0.99c$. Why can't it simply turn on its rocket motor and accelerate up to c, or even faster? A full answer to this question was not given in Einstein's original 1905 paper on relativity, but some years later he showed that as the speed of a spaceship approaches c, adding more energy results in greater momentum but produces smaller and smaller increases in speed.

By using the classical physics formula for change in momentum:

$$F\Delta t_0 = m\Delta v$$

and substituting for proper time, Δt_0, the formula for **relativistic momentum** is simplified to:

$$p_v = \frac{m_0 v}{\sqrt{1 - \frac{v^2}{c^2}}}$$

Assuming an object starts at zero velocity in an observer's reference frame, the final relativistic momentum, p_v. becomes:

$$p_v = \frac{m_0 v}{\sqrt{1 - \frac{v^2}{c^2}}}$$

where

m_0 is the rest mass of the object (kg)

v is the final velocity of the object ($\mathrm{m\,s^{-1}}$)

c is the speed of light ($3 \times 10^8\,\mathrm{m\,s^{-1}}$)

If velocity, v, is needed and the mass and relativistic increase in momentum are known, the formula can be rearranged to give:

$$v = \frac{p_v}{m_0\sqrt{\left(1 + \frac{p^2}{m_0{}^2 c^2}\right)}}$$

The momentum increases very rapidly as a spaceship approaches the speed of light. You might argue that this is expected—after all, momentum is a function of speed. If you graph the relativistic momentum, p_v, against the velocity, v, and on the same graph show the classical momentum, you can see that the relativistic momentum increases at a rate far greater than it would if it were due to the increase in velocity alone (Figure 8.5.3).

Notice too that the classical treatment allows the object to have a speed greater than the speed of light, but the relativistic treatment causes the mass to become very large so that the speed of light is never actually reached.

Now return to the example of the rocket ship that is attempting to increase its speed to the speed of light. With the increase in the relativistic momentum of the rocket ship, it becomes harder for the force of the engines to cause a change in speed. In fact, as the speed approaches c, the relativistic momentum approaches infinity. You can now see why your rocket ship cannot reach the speed of light.

Worked example 8.5.1 illustrates this point. Notice that the result in part **(b)** shows that if you double the impulse required to get the rocket ship to $0.99c$, you will only add $0.007c$ to your top speed. When you've completed Try yourself 8.5.1, consider the change in speed achieved by tripling the impulse.

FIGURE 8.5.2 This rocket ship is moving at $0.99c$ and accelerating, and yet it can never reach a speed of c.

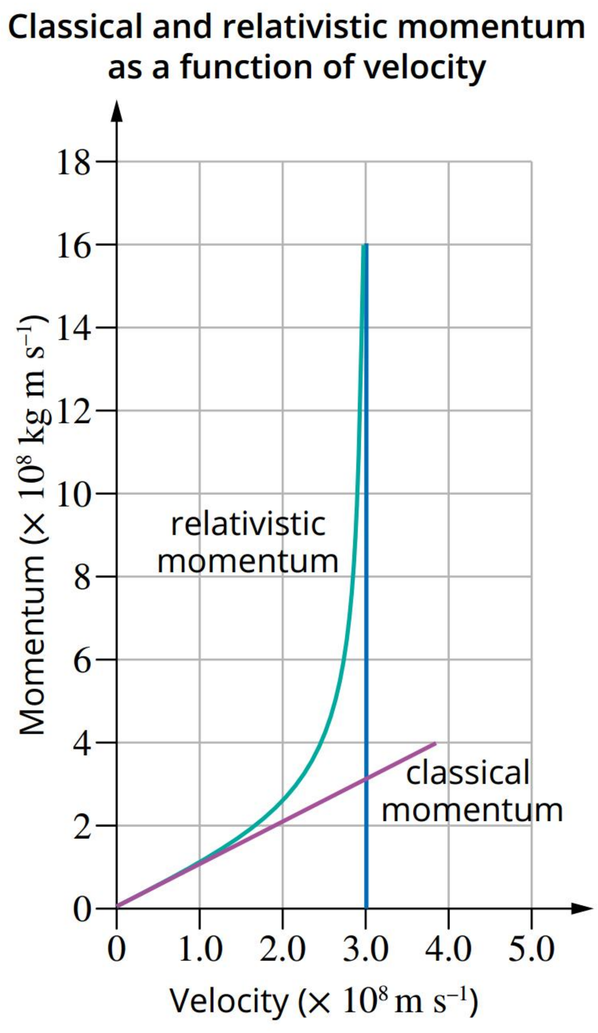


FIGURE 8.5.3 The relationship between classical momentum and velocity, and the relationship between relativistic momentum and velocity, for a 1 kg mass. Note: the blue line represents the speed of light, but according to relativistic momentum, objects will get close but never reach that line, whereas according to classical momentum it is achievable.

Worked example 8.5.1

RELATIVISTIC MOMENTUM

a Calculate the momentum, as seen by Lachie who is stationary, provided to a rocket ship as it travels at a speed of 0.990*c*. The rocket ship has a rest mass of 1000.0 kg.

Thinking	Working
Identify the relativistic momentum formula.	$p_v = \dfrac{m_0 v}{\sqrt{1-\dfrac{v^2}{c^2}}}$
Substitute the values for m_0 and v into the equation and calculate the answer p_v.	$p_v = \dfrac{1000 \times 0.990 \times \left(3 \times 10^8\right)}{\sqrt{1-0.990^2}}$ $= 2.11 \times 10^{12}\,\text{kg m s}^{-1}$

b Calculate the new final speed of the rocket ship in terms of *c* if twice the impulse (change in momentum) of part **a** is applied to the stationary rocket ship.

Thinking	Working
Use the relativistic momentum formula, rearranged.	$v = \dfrac{p_v}{m_0\sqrt{\left(1+\dfrac{p^2}{m_0{}^2c^2}\right)}}$
Determine the change in momentum when twice the impulse is applied.	$p_v = 2 \times 2.1053 \times 10^{12}$ $= 4.21 \times 10^{12}\,\text{kg m s}^{-1}$
Substitute the values for m_0 and p_v into the rearranged equation and calculate the answer v.	$v = \dfrac{4.21\times10^{12}}{1000\sqrt{\left(1+\dfrac{\left(4.21\times10^{12}\right)^2}{1000^2\times\left(3\times10^8\right)^2}\right)}}$ $= 2.99\times10^8\,\text{m s}^{-1}$ $= 0.997c$

➤ Try yourself 8.5.1

RELATIVISTIC MOMENTUM

a Calculate the momentum, as seen by stationary observer Sevda, provided to an electron as it goes from rest to a speed of 0.985*c*. The electron has a rest mass of 9.109×10^{-31} kg.

b Calculate the new final speed of the electron in terms of *c* observed by Sevda if three times the relativistic momentum from part **a** is applied to the electron.

EINSTEIN'S FAMOUS EQUATION

Recall from earlier that relativistic momentum seems to increase towards infinity as the speed gets closer, but never equal, to *c*. As the momentum of an object increases, so does its kinetic energy. The classical relationship between the two can be written as:

$$E_k = \frac{1}{2} m_0 v^2$$
$$= \frac{1}{2} m_0 v \times v$$
$$= \frac{1}{2} pv \text{ or } \frac{p^2}{2m_0}$$

This form of the equation shows that the kinetic energy of an object is related to its momentum as well as its velocity and mass.

Einstein showed, however, that the classical expression for kinetic energy was not correct at high speeds. The mathematics involved is beyond the scope of this course, but Einstein, working from the expression for relativistic momentum and the usual assumptions about work, forces and energy, was able to show that the kinetic energy of an object was given by the expression:

$$E_k = \left(\frac{1}{\sqrt{1 - \frac{v^2}{c^2}}} - 1 \right) m_0 c^2$$

Although it is not very obvious from this expression, if the velocity is small, this expression actually reduces to the classical equation of $E_k = \frac{1}{2} mv^2$. A small velocity in this context means small in comparison to c. But even for speeds up to $0.10c$, the classical expression is accurate to better than ±1%.

Einstein's expression can be expanded to:

$$E_k = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}} m_0 c^2 - m_0 c^2$$

This kinetic energy equation, in turn, can be rearranged as:

$$\frac{1}{\sqrt{1 - \frac{v^2}{c^2}}} m_0 c^2 = E_k + m_0 c^2$$

Einstein interpreted the left-hand side of this expression as being an expression for the total energy of the object:

$$E_{total} = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}} m_0 c^2$$

The right-hand side appeared to imply that there were two parts to the total energy: the kinetic energy, E_k, and another term that only depended on the rest mass, m. The second term, mc^2, he referred to as the rest energy of the object, as it does not depend on the speed of the object. This appeared to imply that somehow there was energy associated with mass, also known as mass–energy equivalence. An astounding proposition to a classical physicist, but, as you have seen, in relativity mass increases as you add kinetic energy to an object. The conservation of energy relationship is therefore:

$$E_{total} = E_k + E_{rest}$$

You will have seen part of this equation before. The conversion of mass into energy, E, can be calculated by:

$\Delta E = \Delta mc^2$

where

ΔE *is* the change in energy (J)

Δm is the change in mass (kg)

c is the speed of light ($m\,s^{-1}$)

This equation tells you that mass and energy are related. In a sense, you can say that mass has energy, and energy has mass. Recall that in Unit 1 this relationship was used to calculate the energy absorbed and released during fission and fusion nuclear reactions.

Worked example 8.5.2

FUSION

Consider the fusion reaction shown below, in which a proton fuses with a deuterium nucleus (a hydrogen nucleus with one neutron) in the Sun. A helium nuclide is formed and a γ ray released. A very small amount of mass is converted to energy. 20.0 MeV of energy is released during this process.

$$^{1}_{1}\text{p} + ^{2}_{1}\text{H} \rightarrow ^{x}_{2}\text{He} + \gamma$$

a Convert the energy released to joules.

Thinking	Working
$1\,\text{eV} = 1.6 \times 10^{-19}\,\text{J}$	$20.0\ \text{MeV} = \left(20 \times 10^{6}\right) \times \left(1.6 \times 10^{-19}\right)$ $= 3.20 \times 10^{-12}\,\text{J}$

b Calculate the amount of mass lost (the mass defect) for this reaction.

Thinking	Working
Use $\Delta E = \Delta mc^2$.	$\Delta m = \dfrac{\Delta E}{c^2}$ $= \dfrac{3.2 \times 10^{-12}}{\left(3 \times 10^{8}\right)^2}$ $= 3.56 \times 10^{-29}\,\text{kg}$

➤ Try yourself 8.5.2

FUSION

A fusion reaction in the Sun fuses two helium nuclides. A helium nucleus and two protons are formed, and a very small amount of mass has been converted to 30.0 MeV of energy.

$$^{3}_{2}\text{He} + ^{3}_{2}\text{He} \rightarrow ^{x}_{2}\text{He} + 2^{1}_{1}\text{H}$$

a Convert the energy released to joules.

b Calculate the amount of mass lost (the mass defect) for this reaction.

8.5 Review

SUMMARY

- Rest mass is the mass of an object as measured in its own reference frame and does not change according to a moving observer.
- In classical physics, the more momentum an object has the more mass or velocity it must have, according to the formula $p = mv$.
- Particles in particle accelerators travelling at near the speed of light experience greater momentum than that calculated by classical physics.
- As an object approaches the speed of light, classical physics is no longer valid as the momentum increase is no longer proportional to the increase in velocity.
- Relativistic momentum for objects approaching the speed of light can be calculated using:

$$p_v = \frac{m_0 v}{\sqrt{1 - \frac{v^2}{c^2}}}$$

- The relativistic momentum equation can be rearranged to find the velocity of an object approaching the speed of light from rest using:

$$v = \frac{p_v}{m_0\sqrt{\left(1 + \frac{p^2}{m_0{}^2c^2}\right)}}$$

- Einstein found that mass and energy are interrelated, and mass–energy equivalence can be calculated using:

$$\Delta E = \Delta mc^2$$

- Mass and energy are seen as different forms of the same thing. This means that mass, m, can be converted into energy, and energy can be converted into mass.

KEY QUESTIONS

Describe

1 State what is meant by rest mass of an object.

2 Particles in particle accelerators demonstrate that relativistic momentum affects particle motion at high speeds. Recall what behaviour demonstrates this.

3 State what would happen to the relativistic momentum of an object, if it were possible, to travel at the speed of light.

4 State the relationship between mass and energy.

Apply

5 Harriet was explaining relativistic momentum to her friend. She said, 'In simple terms, relativistic momentum is larger than classical momentum, because the object has increased in mass." Explain why this definition does not correctly explain relativistic momentum.

6 Compare the relationship between change in velocity and change in momentum for an object travelling at low speeds with an object travelling near the speed of light.

7 Explain how mass–energy equivalence is demonstrated in nuclear reactions.

Analyse

8 Compare the relativistic momentum of the Rosetta spacecraft as observed by the scientists at the European Space Agency with classical momentum. Rosetta has a rest mass of 1230 kg and its speed is $775\,\mathrm{m\,s^{-1}}$.

9 Calculate the energy equivalent of 1.00 kg using the mass–energy relationship.

10 Determine how much mass must be converted for the equivalent of 4.019×10^{-9} J of energy.

8.6 Apparent paradoxes

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- explain the twin paradox and how Einstein resolved it
- identify two apparent paradoxes that arise from the law of simultaneity
- explain how special relativity resolves the flashlights on a train and the ladder in the barn paradoxes.

THE TWIN PARADOX

As discussed in Module 8.3, time in a moving frame seems to pass more slowly. Theoretically you could live long enough to reach distant parts of the universe—if you were travelling at close to the speed of light. Recall from Module 8.3 the scenario of Amaya and Binh riding in a spaceship at speeds close to the speed of light while Clare watched from a space station. According to Clare, Binh and Amaya were moving in slow motion because, according to Clare's observations, time for them has slowed down. However, according to Binh and Amaya, time has slowed down for Clare.

If Clare sees time for Amaya and Binh running slowly, then Amaya and Binh will age more slowly. But if Amaya and Binh see that time for Clare has slowed down, then Clare will age more slowly. So, what happens when Amaya and Binh decide to turn their spaceship around and come home? Who will have aged more?

To solve this paradox, or contradiction, Einstein described a thought experiment in which one of a set of twins heads off on a long space journey while the other twin stays on Earth.

The travelling twin finds that when she returns, her remaining twin has become quite elderly (Figure 8.6.1). Although each twin is in constant motion relative to the other, they both see the other twin aging more slowly; that is, Earth twin sees spaceship twin move away from her, but spaceship twin sees Earth twin move away from her at the same speed. So why did the twin on the spaceship age more slowly than the twin on Earth?

The key to this apparent paradox is that it relies on the symmetry of time dilation: they both see the other twin's clock running slow from their frame of reference. However, this scenario is not symmetrical. Only one twin, the one who stayed on Earth, has spent the entire time in one frame of reference. The twin travelling in the spaceship experienced two frames of reference.

As the spaceship travels away from Earth, both twins see the other twin moving *away* from them in their frame of reference. Then, as the spaceship reaches its destination and begins its journey back, both twins now see the other twin moving *towards* them in their frame of reference. This change in direction means the situation is not symmetrical - only the travelling twin experiences this change in their frame of reference.

While both twins observe the other's clock running slowly due to time dilation, the asymmetry of the situation (one twin staying in a single frame of reference while the other experiences two different frames of reference) resolves the apparent paradox.

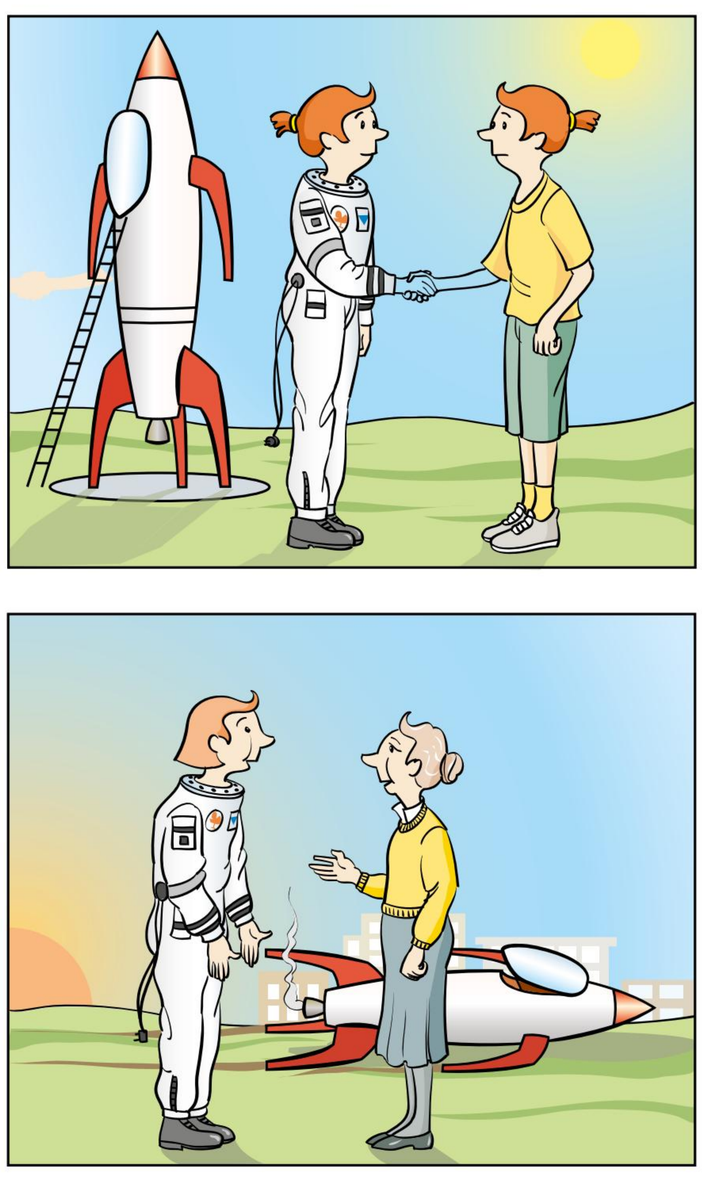


FIGURE 8.6.1 The twin paradox describes the phenomenon where one twin ages less quickly than the other after travelling in two frames of reference at relativistic speeds.

The reason why the twin on the spaceship aged slower is connected to both time dilation and length contraction affecting their journey. From the twin in the spaceship's perspective, the distance they needed to travel appeared shorter due to length contraction, and their clock ran slower due to time dilation. Since they experienced these relativistic effects across multiple frames of reference (moving away and then moving back), the spaceship twin aged less during the total journey.

Although it is called the twin paradox, there is nothing paradoxical about this scenario. It is a direct consequence of how time dilation and length contraction works when comparing events between different frames of reference in special relativity.

This effect has been demonstrated experimentally. In 1971, highly accurate atomic clocks were flown on commercial aircraft around the world. When compared with identical clocks that remained stationary on Earth, the flying clocks showed exactly the time difference predicted by special relativity. This time dilation effect is so well understood that it must be accounted for in modern Global Positioning Systems (GPS) to ensure their accuracy.

FLASHES ON A TRAIN

Recall from Module 8.2 that one of the consequences of accepting the two postulates that Einstein put forward was that two events that are simultaneous for one set of observers may not be simultaneous for another. This led to the apparent paradox of two observers witnessing the same event but reporting different observations. The example in Module 8.2 had Amaya and Binh boarding a train while Clare was outside the train. This train had a flashing light bulb set right in the centre of the carriage where Amaya, Binh and Clare could all view it (Figure 8.6.2).

Amaya and Binh found that the flashes from the light bulb reach the front and back walls at the same time (Figure 8.6.2a); however, Clare, who is watching the same flashes of light, sees the light reach the back wall first (Figure 8.6.2b). In Clare's frame of reference, the back wall is moving towards the light, whereas the front wall is moving away from the light. As the speed of light is the same for all observers in an inertial frame of reference, the light will take longer to reach the further wall as it moves a greater distance from the origin of the flash. Classical physics supported simultaneity and stated this should not happen; an event that is simultaneous for an observer in their frame of reference should be simultaneous to observers in other frames of reference.

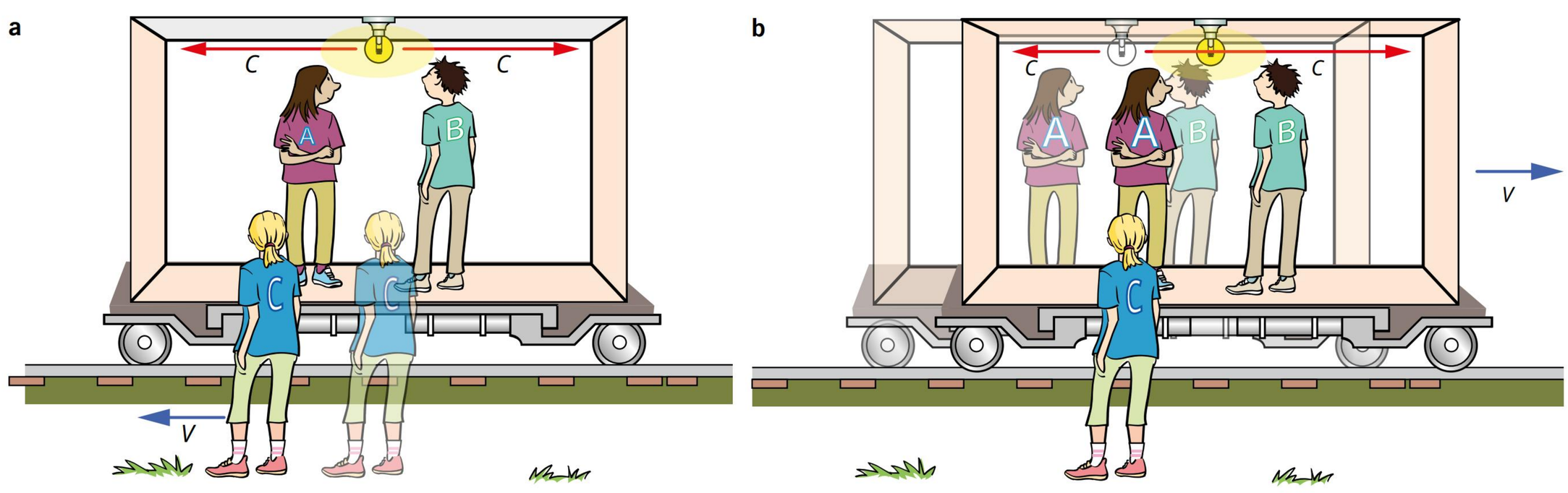


FIGURE 8.6.2 The flashes on a train paradox (a) Amaya and Binh are stationary with the carriage in their frame of reference and see Clare moving past them at high speeds. They see the light flash on the back and front of the carriage at the same time. (b) Clare sees the carriage move past her at high speeds in her frame of reference. The location of the carriage walls has moved before the flash reaches them, so she sees the light flash off the back (closer) wall first and the front (further) wall afterwards.

Einstein said that the only reasonable explanation for this paradox is that time itself is behaving strangely. The amount of time that has elapsed in one frame of reference is not the same as that which has elapsed in another. Special relativity states that simultaneity is relative to the observer.

LADDER IN THE BARN PARADOX

The result of length contraction leads to an interesting phenomenon. Consider the example of the train in the tunnel in Module 8.4. The proper length of the train is 100 m, which means the driver could park the train in the 123 m tunnel. However, when the train is moving at 0.986*c*, it will not fit in the tunnel, as the length of the tunnel is contracted according to the train driver. Similarly, a train that is longer than the tunnel will fit completely inside the tunnel if its length was measured by a stationary observer as the train was moving past very quickly. So, will the train fit? Who is correct? This paradox can be explained using a ladder in a barn.

Observer A is moving a ladder at speeds close to the speed of light towards a barn where observer B is standing. This barn contains two doors, one at the front (where the ladder will enter) and one at the back (Figure 8.6.3). As observer A moves towards the barn, the ladder contracts, and so observer B directs observer A to place the ladder inside the barn. Usually, the ladder does not fit because the barn is too small to contain it. From observer A's point of view, the barn is moving towards him and therefore contracts in the direction of motion, which means that from this view the ladder will not fit inside the barn. Will the ladder fit or not? As discussed in the paradox of flashes of light on a train, in relativity, simultaneity is relative to the observer. This means the question of whether the ladder fits inside the barn is relative to each observer. As simultaneity is relative, the two doors did not need to be shut at the same time, and the ladder did not need to fit inside the barn.

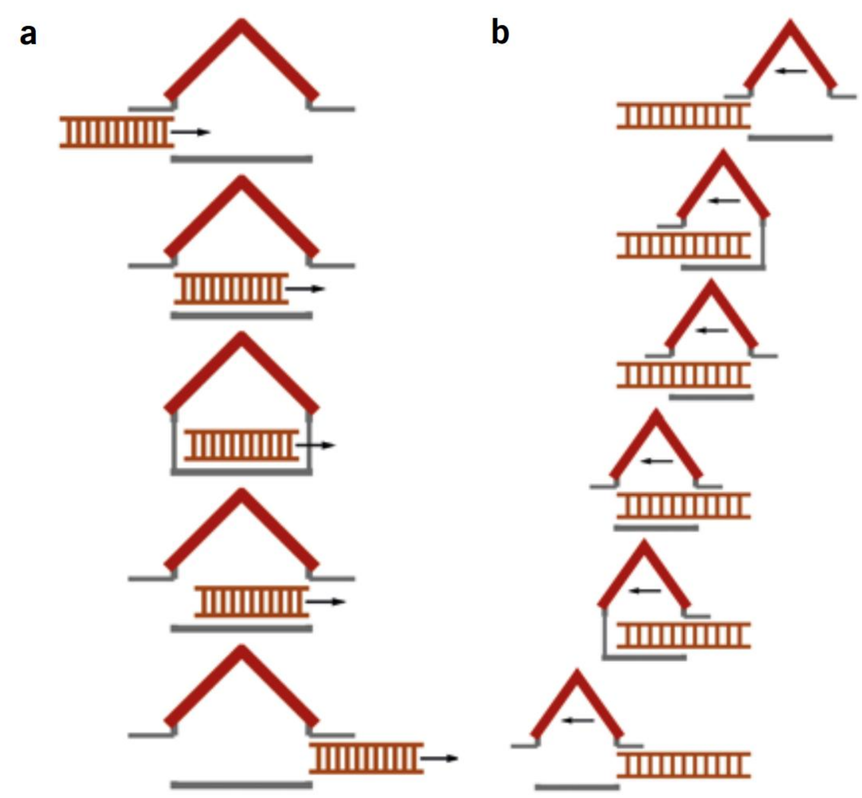


FIGURE 8.6.3 The ladder in the barn paradox (a) The ladder relative to the observer near the barn (observer B). The ladder's length appears contracted. (b) The ladder relative to the observer carrying the ladder (observer A). The barn's length appears contracted.

8.6 Review

SUMMARY

- Time dilation and length contraction give rise to several apparent paradoxes, all of which can be explained by special relativity.
- Two events that are simultaneous in one frame of reference are not necessarily simultaneous in another.
- Observers in relative motion both see time slowing in the other frame of reference, that is, each sees the other age more slowly.
- The twin paradox is explained by Einstein as the twin in the spaceship experienced two frames of reference, which meant they were the moving observer who experienced time dilation.
- The flashlights on the train and ladder in a barn paradoxes are explained by simultaneity being relative to the observer.

KEY QUESTION

Describe

1 State why you can say in the twin paradox explanation that the twin who stays at home ages faster than the twin who goes on the journey.

2 Recall what happens to object length for two observers moving relative to each other.

3 State a limitation of simultaneity between frames of reference.

Apply

4 Describe how a stationary observer and a moving observer could each claim that time is running more slowly for the other.

5 Explain using frames of reference how the flashlights on a train paradox demonstrates time dilation. Identify which observer is measuring proper time and which observer is measuring dilated time.

6 Explain using frames of reference how the ladder in the barn paradox demonstrates length contraction. Identify which observer is measuring proper length and which observer is measuring contracted length.

Analyse

7 Explain how special relativity is able to resolve the flashlights on a train and ladder in a barn paradoxes.

8 Explain why the twin in the spaceship ages less than the twin on Earth using only reference frames.

Chapter review

08

KEY TERMS

aether
atomic clock
classical physics
frame of reference
inertial frame of reference
length contraction
medium
muon
non-inertial frame of reference
postulates of special relativity
proper length
proper time interval
relativistic length
relativistic momentum
relativistic time interval
rest mass
simultaneity
simultaneous
time dilation

KEY QUESTIONS

Describe

1 Recall the postulates of special relativity by selecting the best description from the options below:

A Light always travels at $3 \times 10^8\,\mathrm{m\,s^{-1}}$ through all media.

B Absolute velocity is that measured with respect to the Sun.

C Velocities can only be measured relative to something else.

D It is possible to determine how fast you are going without seeing what is around you.

2 Spaceships A and B depart Earth and travel together at a speed of 0.99*c* towards planet Earth. The crew on Spaceship A see a person on Earth moving in slow motion. Identify the option that describes how the observer on Earth sees the crew of both Spaceship A and B.

A Both crews appear to have sped up.

B Both crews appear to have slowed down.

C The crew on Spaceship A appears to be moving at normal speed, the crew on Spaceship B appears to have sped up.

D The crew on Spaceship A appears to be moving at normal speed, the crew on Spaceship B appears to have slowed down.

3 Identify the condition in which the twin who stays at home ages faster than the twin who goes on the journey.

A while observing the spaceship twin's outward journey only

B while observing the spaceship twin's return journey only

C while observing the spaceship twin's change in direction only

D while observing the spaceship twin's entire journey only

4 Recall why classical physics cannot explain how muons created in the upper atmosphere reach Earth's surface.

5 State why it is impossible to measure the absolute velocity of an object.

6 Identify whether special relativity can be used to analyse the movement of a satellite travelling at near the speed of light as it orbits Earth.

7 Recall what is significant about the properties of energy and mass in the energy-mass equivalence formula, $\Delta E = \Delta mc^2$.

Apply

8 Identify one or more of the following conditions that is sufficient to ensure the proper time between two events is measured. The observer must:

A be stationary

B be in the same frame of reference

C not be accelerating with respect to the frame of the two events

D be in a frame of reference that is travelling at the same velocity as the frame of the two events

9 Determine which statement is incorrect if you were travelling at high speeds (0.99*c*). Explain your answer.

A Your heart rate is slower than normal.

B You will have a normal life expectancy.

C You will age slower than a person on Earth.

D Time runs normally in your frame of reference.

10 Imagine that Amaya is at the front end of a train carriage moving backwards at $10.0\,\mathrm{m\,s^{-1}}$. She shines a laser towards Binh, who is at the other end of the carriage. Clare is watching all of this from the side of the track. Compare the speed of the light as measured by Clare with that measured by Binh.

11 You are riding in a very smooth, quiet train with the blinds drawn. Explain how or whether you could tell the difference between the train:

a being stopped in the station

b accelerating away from the station

c travelling at a constant speed.

12 Describe what happens to simultaneity as objects approach the speed of light. Explain your reasoning.

13 Explain why a small mass defect in nuclear fission or fusion reactions can produce a significant amount of energy.

Analyse

14 Akshay is sitting in a very fast jet plane and looking out of the window at a clock placed on top of a mountain. He notes that a goat takes 20.0 s to run along a rocky ridge using the clock on the mountain. Calculate how much time has passed on Akshay's clock if the plane is flying at a speed of $2.00 \times 10^8\,\mathrm{m\,s^{-1}}$.

15 A high-speed, subatomic particle is accelerated by a linear accelerator to a speed of $2.83 \times 10^8\,\mathrm{m\,s^{-1}}$. A researcher measures that it only leaves, on average, a track that is 2.50 cm long in the bubble chamber. Determine the mean lifetime of the same particle if it were at rest relative to the researcher and her timer.

16 Calculate the relativistic momentum of a carbon-12 nucleus in the solar wind if its rest mass is $1.992\,648\,24 \times 10^{-26}$ kg and it is travelling at a speed of $800.0\,\mathrm{m\,s^{-1}}$. Compare this value with that calculated by classical momentum.

17 A space shuttle is travelling at close to $8000\,\mathrm{m\,s^{-1}}$. Imagine that, as it travels east–west, it takes a photograph of Australia, which is close to 4000 km wide. Because of its speed, the space camera will see everything on Earth slightly contracted.

a Determine approximately how much less than 4000 km wide will Australia appear to be in this photograph.

b Deduce whether the north–south dimension of Australia will be smaller as well.

18 Imagine that, as you watch a space traveller journeying from Earth to the star Vega travelling at 99.5% of the speed of light, you see their clock slow down by a factor of about 10 times. Vega is about 25.0 light-years from Earth so, in your frame of reference, it takes light from Vega 25.0 years to reach Earth.

a Calculate how long it will take the traveller to reach Vega in Earth's frame.

b Predict how long it takes the traveller to travel to Vega according to them.

c Determine if your answer to part **b** implies that they were able to get to Vega in less time than light. Explain your answer.

Interpret

19 Rest masses of particles can also be expressed in units of $\mathrm{MeV\,c^{-2}}$ or $\mathrm{GeV\,c^{-2}}$. This is the energy equivalent (in MeV or GeV) of the particle's mass.

a Prove that the equivalent mass in $\mathrm{eV\,c^{-2}}$ of a particle of rest mass m_0 in kg can be written as

$$m_0 = \frac{E}{e}(\text{in eV c}^{-2})$$

where E is the energy equivalent in joules and e is the elementary charge 1.602×10^{-19} C.

For example, the equivalent mass of a single electron in $\mathrm{eV\,c^{-2}}$ ($m_0 = 9.11 \times 10^{-31}$ kg) is $5.118 \times 10^5\,\mathrm{eV\,c^{-2}}$, or $511.8\,\mathrm{keV\,c^{-2}}$.

Calculate the equivalent mass of the following particles in $\mathrm{eV\,c^{-2}}$:

b a proton of rest mass 1.673×10^{-27} kg

c an alpha particle of rest mass $6.644\,657 \times 10^{-27}$ kg.

20 The Sun has a power output of 3.828×10^{26} W. Predict how much matter must be converted into energy each second to sustain the Sun's power based on this information.

21 A group of space voyagers is travelling to the star Sirius, which is 8.6 light-years away, at 90.0% of the speed of light. One light-year is equivalent to 9.46×10^{15} km.

The spaceship sends out a radio signal, at a frequency of 4.5×10^5 Hz, from Sirius back to Earth to say they have arrived. Decide on a frequency that the people on Earth must tune into to receive the signal. Assume that the signal was sent just before the spaceship slowed down to land on a planet orbiting Sirius.

Data analysis

DATA SET 1

The information below applies to Questions **1–4**

An experiment was conducted to address the following research question:

What is the relationship between the mass lost during the nuclear decay and the energy released?

The experimental data was collected and processed, and is presented in the table below.

Mass defect (kg)	Energy released (J)			Average energy released (J)
	Trial 1	Trial 2	Trial 3	
6.67×10^{-27}	6.02×10^{-10}	6.05×10^{-10}	6.00×10^{-10}	$6.02 \times 10^{-10} \pm 2.50 \times 10^{-12}$
3.83×10^{-27}	3.42×10^{-10}	3.45×10^{-10}	3.43×10^{-10}	$3.43 \times 10^{-10} \pm 1.50 \times 10^{-12}$
2.08×10^{-27}	1.88×10^{-10}	1.85×10^{-10}	1.86×10^{-10}	
1.91×10^{-27}	1.72×10^{-10}	1.70×10^{-10}	1.71×10^{-10}	$1.71 \times 10^{-10} \pm 1.00 \times 10^{-12}$

Question 1 (2 marks)

Calculate the mean and absolute uncertainty of the mean for the 2.08×10^{-27} kg data.

Question 2 (2 marks)

Identify the trend between mass defect and energy released. Use evidence from the table to support your answer.

Question 3 (2 marks)

Determine the speed of light for the 3.83×10^{-27} kg data.

Question 4 (3 marks)

Predict the amount of energy released for a mass defect of 3.34×10^{-27} kg.

Verify if this value matches the trend discussed in Question **2**.

CHAPTER 09

Quantum physics

Quantum theory explains the behaviour of very small things in the universe including photons and electrons. The quantum world is quite different from the everyday world, which is explained by the laws of classical physics.

The nature of light has been discussed and debated since the time of Isaac Newton in the 17th century. The debate arose because light displays characteristics of waves in some contexts and characteristics of particles in others. Quantum theory was developed during the 20th century and described light as photons—quantised packets of energy. Along with relativity, quantum theory forms part of modern physics.

The behaviour of light is important for fibre optics and the optical storage of information, while the quantum behaviour of electrons is important in understanding the behaviour of the semiconductors that make up computer components, including chips, diodes and transistors.

Syllabus subject matter

Topic 2 • Quantum theory

QUANTUM THEORY

- Explain how the double slit experiment provides evidence for the wave model of light. **9.1**
- Describe light as an electromagnetic wave. **9.1**
- Explain the concept of black-body radiation and the significance of the evidence it provides. **9.2**
- Describe the photoelectric effect in terms of the photon. **9.3**
- Describe the concepts of threshold frequency and work function. **9.3**
- Solve problems involving black-body radiation and the photoelectric effect using $\lambda_{max} = \frac{b}{T}$, $E = hf = \frac{hc}{\lambda}$, $E_k = hf - W$, $W = hf_0$ and $\lambda = \frac{h}{p}$. **9.2, 9.3**
- Interpret data related to the photoelectric effect. **9.3**

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9.1 Light as a wave

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- outline the evidence that supports the wave nature of light
- perform calculations relating the energy, wavelength and frequency of light
- list forms of radiation that make up the electromagnetic spectrum
- perform calculations of the wavelength of light based on the double-slit experiment.

In *Pearson Physics Queensland Units 1 & 2* Chapter 11, you were introduced to light as a **wave** and the nature of electromagnetic radiation (EMR) was discussed in Chapter 7 of this book. In brief, if a changing electric field is produced—for example, by a charged particle moving backwards and forwards—then this changing electric field will produce a changing magnetic field at right angles to it (Figure 9.1.1).

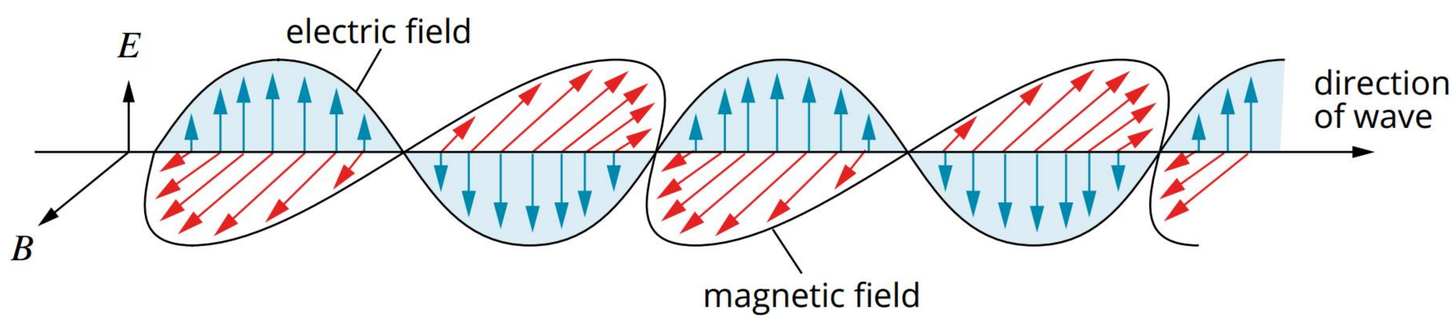


FIGURE 9.1.1 The electric and magnetic fields in electromagnetic radiation are perpendicular to each other and both are perpendicular to the direction of propagation of the radiation.

The changing magnetic field will, in turn, produce a changing electric field and the cycle will be repeated. In effect, this produces two mutually propagating fields and thus the electromagnetic radiation can extend outwards into space at the speed of light. Both the electric and magnetic fields oscillate at the same frequency: the frequency of the light wave. Forms of electromagnetic radiation include **visible light**, **infrared** and **ultraviolet** radiation, radio waves, microwaves, X-rays and gamma rays.

While the focus has so far been on the wave model of light, a second model will be introduced in this chapter and Chapter 10. Light can also be modeled as a particle, and these two models complement each other in explaining various phenomena. The integration of both models is known as the wave-particle duality of light.

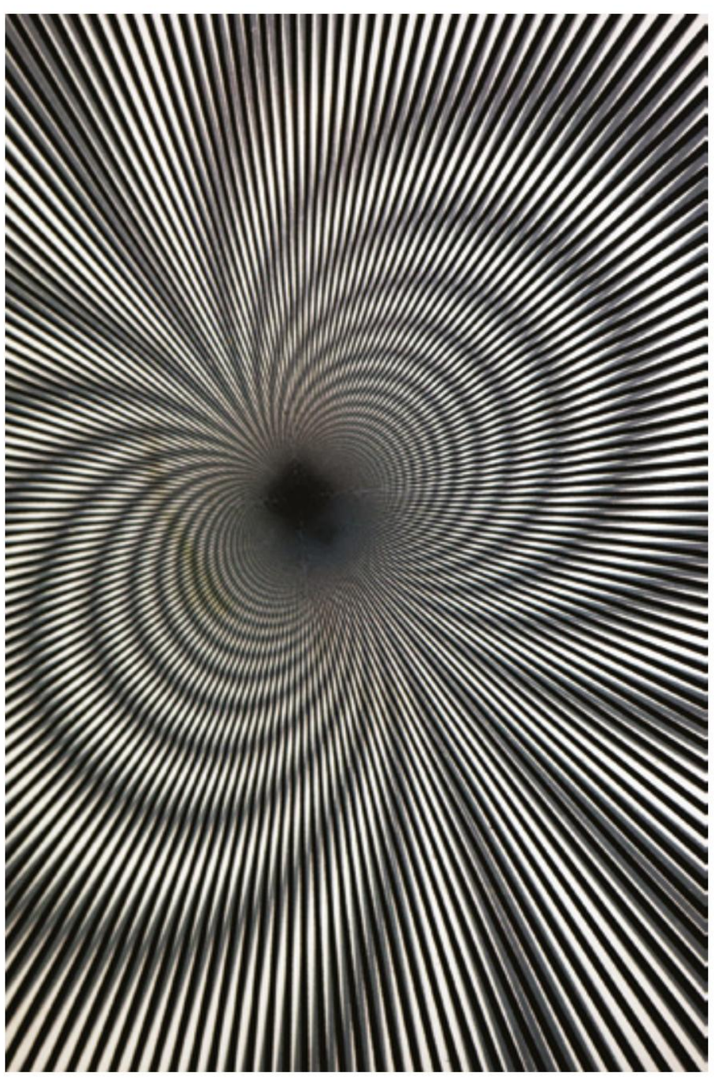


FIGURE 9.1.2 Optical interference can produce spectacular patterns.

THE DOUBLE-SLIT EXPERIMENT

Between the 17th and 19th centuries, most scientists considered light to be a stream of particles. This idea was based on the 'corpuscular' theory proposed by Sir Isaac Newton.

In 1803, an English scientist called Thomas Young performed a now-famous experiment, the **double-slit experiment**, in which he shone monochromatic light on a screen containing two very tiny slits. On the far side of the double slits he placed another screen on which he observed the pattern produced by the light passing through the slits. Young's observation of **interference** patterns in light, where multiple waves form a resultant pattern of optical interference (Figure 9.1.2), was a pivotal moment in the history of science. It tipped the scales in a long-running dispute between scientists about the nature of light, and paved the way for a series of discoveries and inventions that fundamentally changed scientists' understanding of energy and matter.

According to the particle model, light should have passed directly through the slits to produce two bright lines or bands on the screen (Figure 9.1.3a). Instead, Young observed a series of bright and dark bands or 'fringes' (Figure 9.1.3b).

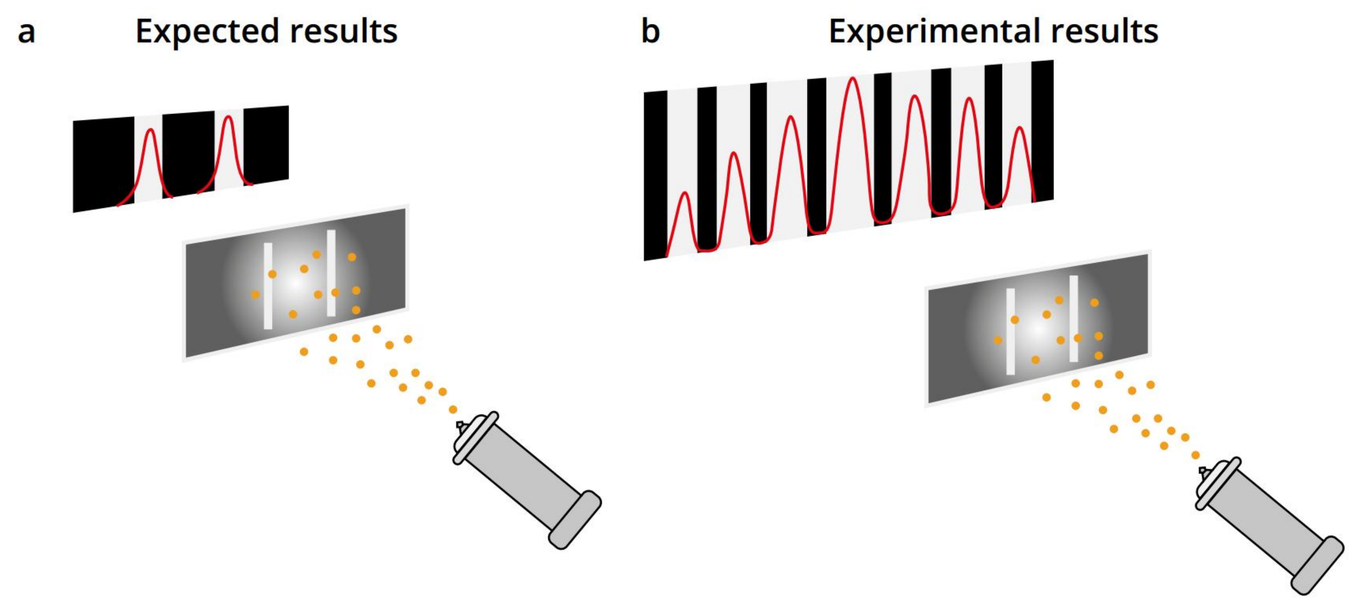


FIGURE 9.1.3 (a) The expected results based on the particle model, which predicts that light produces a bright band for each slit (b) The actual experimental results, which produces a series of bright and dark bands or 'fringes'

Young was able to explain this bright and dark pattern by treating light as a wave. He assumed that the monochromatic light was like plane waves and that, as they passed through the narrow slits, these plane waves were diffracted into **coherent** (in phase) circular waves as shown in Figure 9.1.4a. The circular waves would interact, causing interference. The interference pattern produced by these two waves would result in lines of **constructive** (antinodal) and **destructive** (nodal) **interference** that would match the bright and dark fringes respectively. Earlier in his scientific career, Young had observed similar interference patterns in water waves (Figure 9.1.4b). This gave greater credibility to the wave model for light proposed by Christiaan Huygens and Robert Hooke many years earlier.

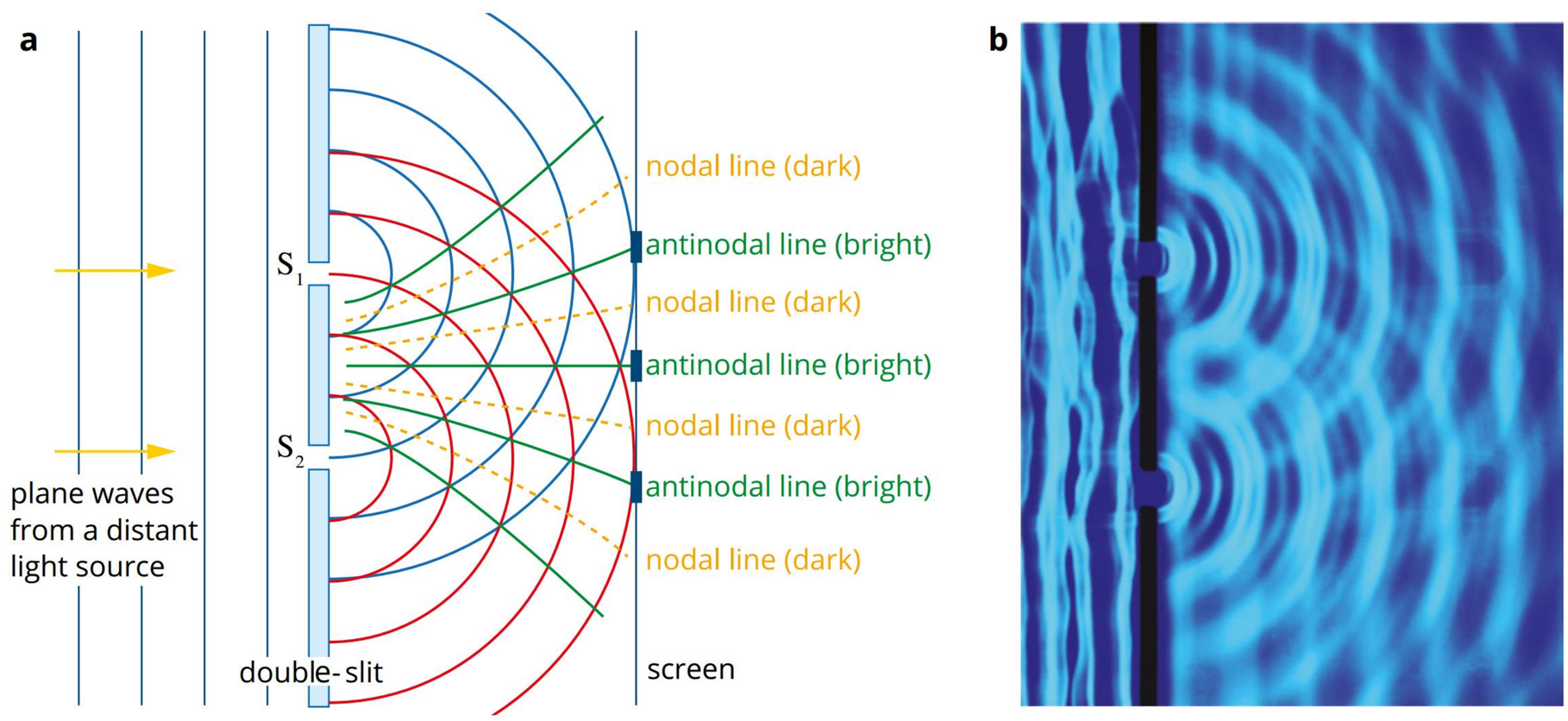


FIGURE 9.1.4 (a) The interaction of two circular waves can produce a pattern of antinodal (constructive interference) and nodal (destructive interference) lines. (b) Interference patterns can be observed in water waves.

Figure 9.1.5 shows the light intensity pattern of the bright and dark fringes. When Young used his data to calculate the wavelength of light, it became clear why no one had ever noticed the wave properties of light before—light waves have tiny wavelengths, with typical values of less than 1 micrometre (1 μm = 0.001 mm).

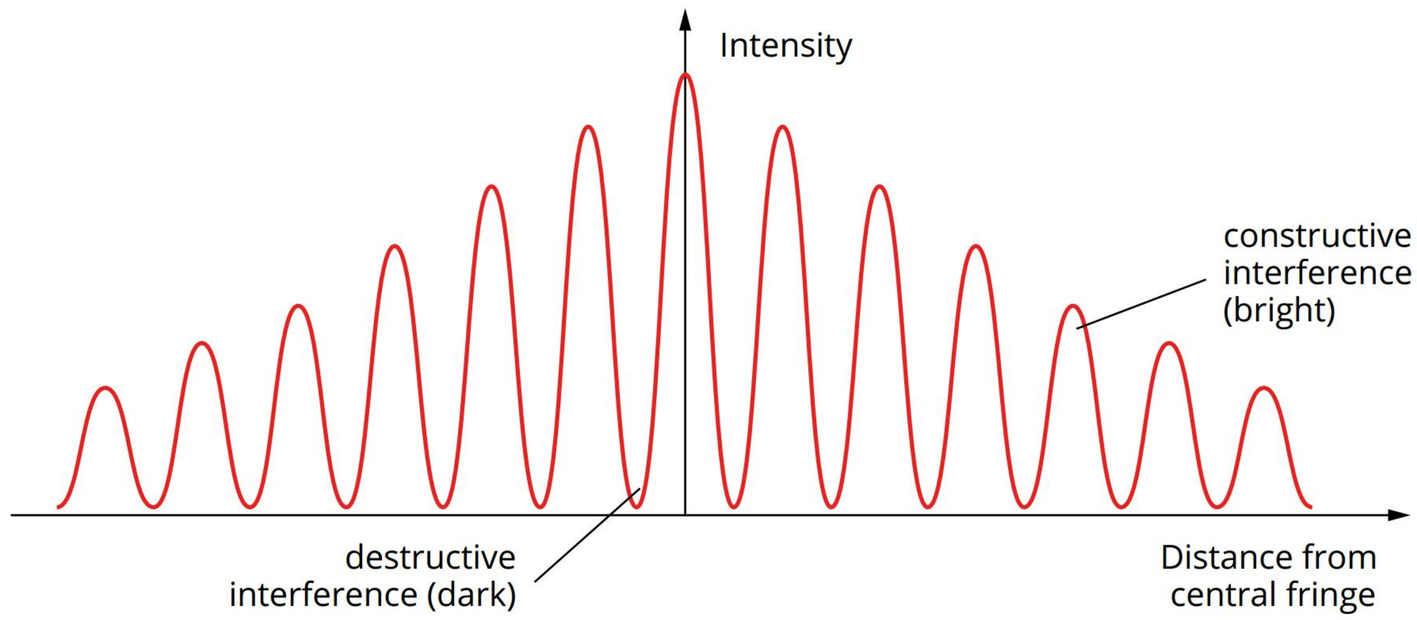


FIGURE 9.1.5 The double-slit interference pattern can be considered in terms of an intensity distribution graph. The horizontal axis represents a line drawn across the screen. The centre of the distribution pattern corresponds to the centre of the brightest central fringe, the central maximum.

9.1 Review

SUMMARY

- The double-slit experiment provided evidence to support the wave model of light.
- Young observed interference patterns in light which were similar to interference patterns seen in water waves.

KEY QUESTIONS

Describe

1. According to the particle model of light, the double-slit experiment should have produced two bright lines on the screen. Describe what was actually observed on the screen.
2. Recall the two models of light.
3. In the wave model of light, state the two waves that are perpendicular to each other.
4. Sketch the pattern of light seen when the double slit experiment is performed.

Apply

5. In Figure 9.1.4 bright fringes are found when a crest of a wave from S_1 intersects a crest of a wave from S_2. Explain what is happening when two waves interfere to produce a fringe that is about 50% of the intensity of the bright fringes.

Analyse

6. Discuss reasons why the double-slit experiment and Young's interpretation of the results were considered so revolutionary at the time when it occurred.

9.2 Black-body radiation

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- state Wien's displacement law
- perform calculations using $\lambda_{max} = \frac{b}{T}$
- describe the differences between absorbed and emitted radiation
- describe how a quantum view of the nature of light includes both particle and wave characteristics
- identify that black-body radiation provides evidence that electromagnetic radiation is quantised into discrete values.

Electromagnetic radiation (EMR) is emitted by all objects and systems. The EMR is emitted in a continuous spectrum, with a peak wavelength or frequency that depends almost entirely on the temperature of the object and not on the characteristics of the material itself.

The higher the temperature of an object or system, the higher the frequency, and the shorter the wavelength of the emitted radiation. As temperature increases, electromagnetic radiation is emitted at increasingly higher frequencies. Consider the following examples:

- Cool objects, such as the human body, emit radiation at long wavelengths with lower energy, such as infrared radiation. Infrared radiation is not visible to the naked human eye under normal circumstances.
- At higher temperatures, objects emit radiation with a higher frequency, and you can see them glow red. An example is a bar heater that glows red hot.
- At even higher temperatures, say 2000 K, objects such as the filament of an incandescent light glow yellow or white.
- Very hot objects, at temperatures of 10^6 K or more, emit most of their radiation within the gamma and X-ray regions of the electromagnetic spectrum.

WIEN'S DISPLACEMENT LAW

Wilhelm Wien, a German physicist, formulated laws that describe the properties of heat radiation. Wien discovered that the peak wavelength at which an object will emit the maximum intensity of radiation is dependent on its surface temperature. Wien's displacement law, commonly known as Wien's law, can be used to determine the peak wavelength for an object at a particular surface temperature.

Wien's displacement law states that

$$\lambda_{max} = \frac{b}{T}$$

where

λ_{max} is the peak wavelength of the emitted radiation (m)
b is a constant $= 2.898 \times 10^{-3}$ m K
T is the surface temperature of the object in kelvins (K).

Rearranging this equation into the form $\lambda_{max} T = b = 2.898 \times 10^{-3}$ m K shows that, no matter what the surface temperature of an object, the product of the temperature and the wavelength at which the peak intensity of the emitted radiation occurs is a constant and is equal to about 2.898×10^{-3} m K.

The graph in Figure 9.2.1 shows the continuous spectrum emitted by any solid, liquid or even a dense gas at particular temperatures. An object at a temperature of about 12 000 K will emit its peak wavelength in the ultraviolet range. That is, the wavelength corresponding to the highest intensity for the 12 000 K curve will occur in the ultraviolet range.

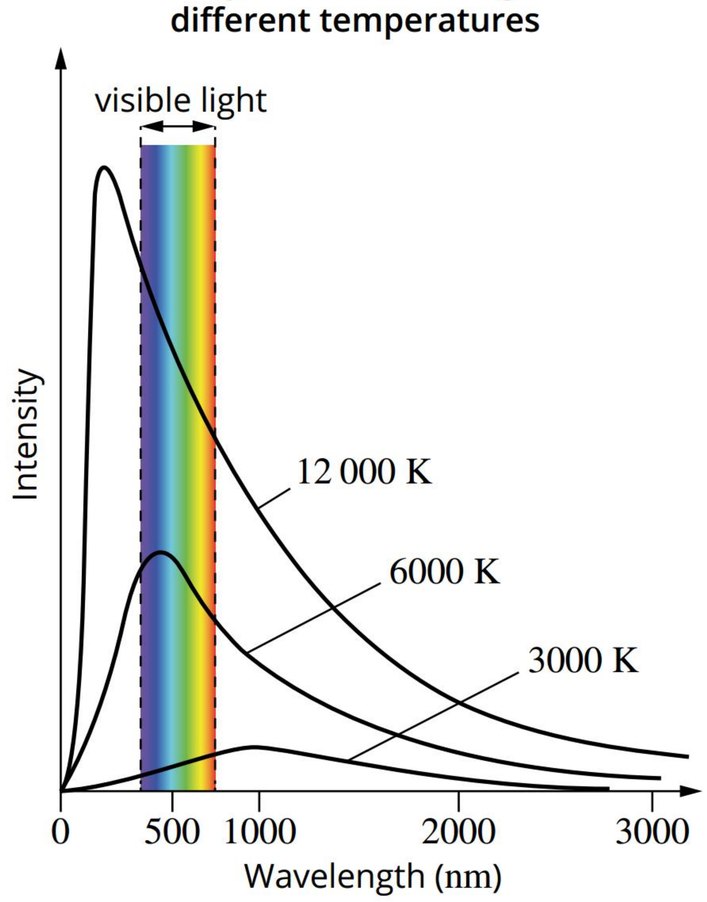


FIGURE 9.2.1 The spectrum of wavelengths emitted at different temperatures. The radiation approximates the surface temperature of many real objects.

The 6000 K curve in the graph in Figure 9.2.1 corresponds to the surface temperature of the Sun. The intensity maximum corresponds to a peak wavelength within the visible band of the electromagnetic spectrum, at about 500 nm.

The surface temperature of the Sun means that the electromagnetic radiation emitted by the Sun peaks in the visible range and is emitted mainly within the range between ultraviolet and infrared, including visible light.

Black-body radiation

Wien's work on the wavelength of the radiation emitted by a hot, dense object was based initially on a theoretical object called a **black body**. A black body does not necessarily have to be black. An incandescent lamp or a light bulb may be, to a certain extent, regarded as a black body.

This theoretical object completely absorbs all the rays of electromagnetic radiation incident on it regardless of the wavelength of the radiation. In other words, a black body does not reflect any radiation. The radiation emitted by many objects, such as the Sun, can be approximated as the radiation emitted by a black body at the same temperature. Figure 9.2.1 is based on the wavelengths emitted by a black body. The spectrum emitted by a hot solid, liquid or dense gas is continuous, but has a peak intensity at a wavelength inversely proportional to the surface temperature. This relationship is more simply stated by rearranging Wien's displacement law:

$$\lambda_{max} \propto \frac{1}{T} \text{ and also } T \propto \frac{1}{\lambda_{max}}$$

Wien's displacement law makes it possible to determine the approximate temperature of stars, assuming that they emit radiation similar to that emitted by a black body. During astronomic observations, it was discovered that stars at different temperatures have peaks in the graph of their emissive power at different wavelengths. When the wavelength that corresponds to the peak of the power emitted by a star is known, the temperature of the star can be found by applying Wien's displacement law.

Worked example 9.2.1

THE TEMPERATURE AT A STAR'S SURFACE

The Sun emits a continuous electromagnetic spectrum with a peak wavelength of approximately 500 nm. Estimate the surface temperature of the Sun based on the peak wavelength.

Thinking	Working
Express the peak wavelength in metres.	$\lambda_{max} = 500\,\text{nm} = 5.0 \times 10^{-7}\,\text{m}$
Rearrange Wien's displacement law to solve for T.	$\lambda_{max} = \frac{b}{T}$ $\lambda_{max}T = 2.898 \times 10^{-3}\,\text{m K}$ $T = \frac{2.898 \times 10^{-3}}{\lambda_{max}}$
Substitute the value for λ_{max} and solve for T.	$T = \frac{2.898 \times 10^{-3}}{5.0 \times 10^{-7}}$ $= 5796\,\text{K}$

➤ Try yourself 9.2.1

THE TEMPERATURE AT A STAR'S SURFACE

A newly discovered star is observed to have a peak emitted radiation wavelength of approximately 90 nm. Estimate the surface temperature of this star based on this wavelength.

Re-radiated electromagnetic radiation

Radiant energy interacts with matter in three ways. It can be:

- reflected
- transmitted
- absorbed.

In most cases, it will be a combination of two or more of these modes. For example, absorption of radiant energy by the surface of Earth leads to the heating of the surface and re-radiation of radiant energy.

Earth's atmospheric gases absorb very narrow wavelengths of the incoming solar radiation, depending upon the nature of the gas. The smaller molecules of oxygen and nitrogen absorb very short wavelengths of solar radiation. The larger molecules of water vapour and carbon dioxide absorb primarily longer infrared radiant energy. About 17% of the radiant energy from the Sun is absorbed by the atmosphere, leading to the heating of the upper layers of the atmosphere.

The lower layers of the atmosphere are not predominately heated by the Sun's radiant energy but, rather, by radiation from the surface of Earth. Earth is much cooler than the Sun and so emits much longer wavelength radiation. With the temperature of the Sun's surface being approximately 6000 K, the peak wavelength of solar radiation is about 500 nm. This corresponds to the visible part of the electromagnetic spectrum. Earth has an average temperature of about 16°C or 289 K. At that significantly lower temperature, Earth emits most of its energy in the infrared range of the electromagnetic spectrum. This can be seen in the infrared image in Figure 9.2.2.

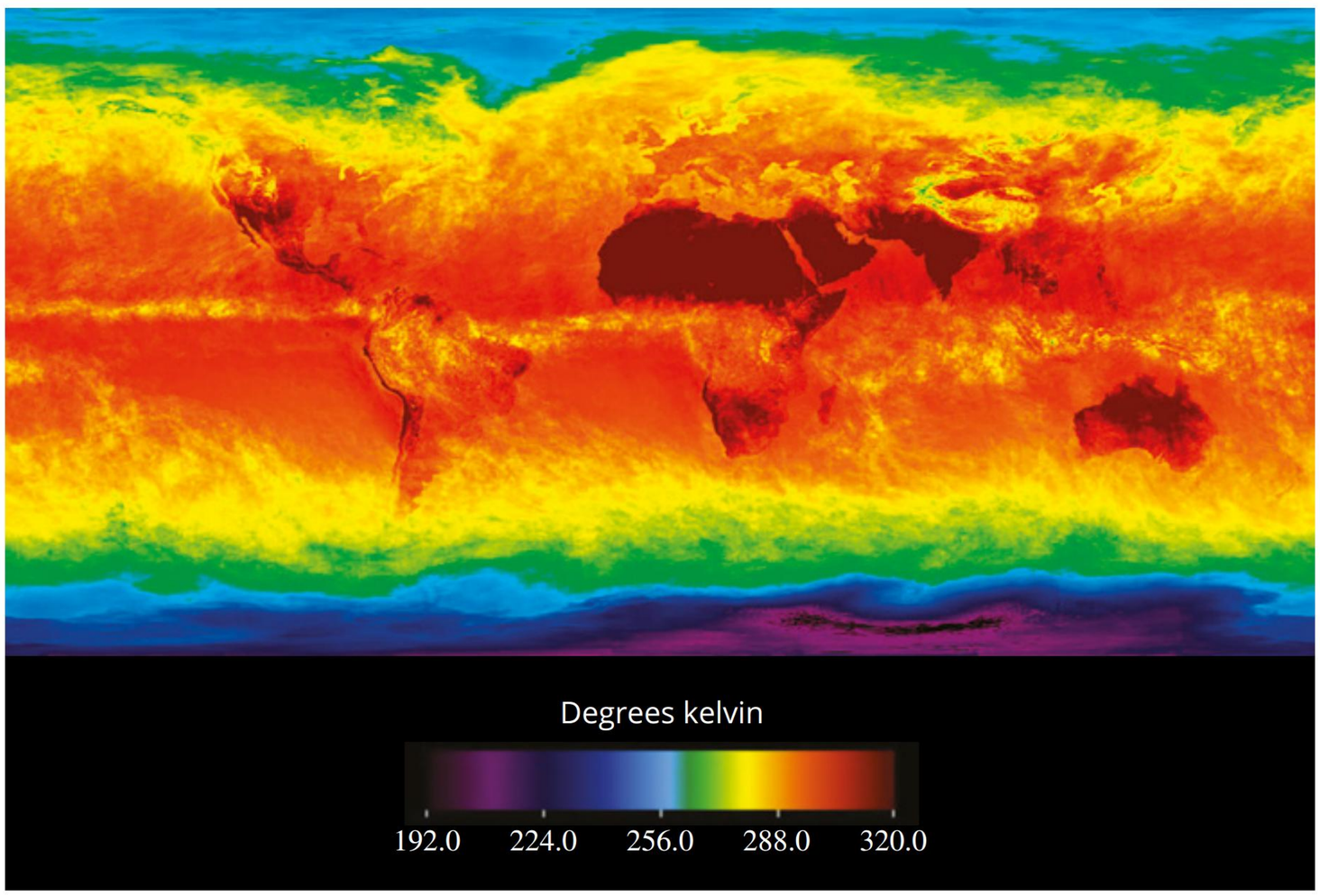


FIGURE 9.2.2 The Atmospheric Infrared Sounder (AIRS) instrument aboard NASA's Aqua satellite senses temperature using infrared wavelengths. This image shows the temperature of Earth's surface or clouds covering it for the month of April 2003.

If Earth is modelled as a black body, the peak wavelength of re-radiated energy from Earth can be calculated using Wien's displacement law.

Worked example 9.2.2

RE-RADIATED ENERGY FROM EARTH

Earth's average surface temperature is 289 K. Calculate the peak wavelength of the re-radiated electromagnetic radiation.	
Thinking	**Working**
State Wien's displacement law.	$\lambda_{max} = \frac{b}{T}$ $= \frac{2.898 \times 10^{-3}}{T}$
Substitute the value for T and solve for λ_{max}.	$\lambda_{max} = \frac{2.898 \times 10^{-3}}{289}$ $= 1.00 \times 10^{-5}\,\text{m} = 10.0\,\mu\text{m}$

➤ Try yourself 9.2.2

RE-RADIATED ENERGY FROM EARTH

The average surface temperature at Earth's equator is 300.0 K. Calculate the peak wavelength of the re-radiated electromagnetic radiation from this part of Earth.

The ultraviolet catastrophe

Wein and his contemporaries studied black-body radiation extensively, leading to Wein's displacement law, which was derived empirically (from experimental results). However, when physicists attempted to predict black-body radiation using the wave-based theories of the time, it was found that these predictions incorrectly suggested that the energy emitted by a body would increase to infinity at very small wavelengths. This was referred to as the 'ultraviolet catastrophe'. Clearly, it was not the case. German physicist Max Planck came up with an equation that matched the experimental results, by assuming that the radiation from a black body could only be emitted in discrete packets. In the next module, you will learn more about Planck's work on the quantisation of energy.

9.2 Review

SUMMARY

- Electromagnetic radiation is emitted in a continuous spectrum by all objects whose temperature is above absolute zero.
- The peak wavelength at which an object will emit the maximum intensity of radiation is dependent on the object's surface temperature and is given by Wien's displacement law. Wien's law states that $\lambda_{max} = \frac{b}{T}$, where $b = 2.898 \times 10^{-3}$ m K.
- The surface temperature of the Sun is approximately 6000 K. This means that the electromagnetic radiation emitted by the Sun peaks in the visible range and is emitted mainly within the range between ultraviolet and infrared light.
- The average surface temperature of Earth is approximately 289 K. Re-radiated energy from Earth will lie in the infrared section of the electromagnetic spectrum. The peak wavelength can be calculated using Wien's displacement law.

KEY QUESTIONS

Describe

1 State Wien's displacement law.

2 Explain what is meant by black-body radiation.

3 Describe the ultraviolet catastrophe.

Apply

4 Calculate the temperature of the surface of a star, if the star emits a continuous electromagnetic spectrum with a peak wavelength of 800.0 nm.

5 The element of an electric heater is just seen to glow a dull red. This colour corresponds to the lower end of the visible spectrum at 700.0 nm. Calculate the temperature, in K, of the element of the heater.

6 The peak wavelength emitted by hot lava is 1.97 μm, calculate the temperature of the lava in kelvin.

7 Calculate the peak wavelength of the energy being emitted by the star if a star has a surface temperature of 9320 K.

8 The universe has an average temperature of 2.7 K. This background temperature is detected as cosmic microwave background radiation (CMBR). What is the wavelength of the radiation scientists measure as CMBR?

9 The human body has a temperature of 37° C, determine the peak wavelength emitted by the human body.

9.3 The photoelectric effect

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- state Planck's equation
- perform calculations using Planck's equation in both joules (J) and electron volts (eV)
- describe the features of the photoelectric effect, including work function, kinetic energy of electrons and the effect of frequency
- explain the features of the photoelectric effect using a quantum model of the nature of light
- interpret data related to the photoelectric effect.

By the end of the 19th century, most scientists had accepted that the wave model of light had replaced the particle model. The wave model explained a number of phenomena (such as diffraction, interference and polarisation) that could not be explained using the particle model. The wave model's inability to explain a couple of key observations was unexpected, leading to a fundamental revolution in the understanding of both light and matter.

PLANCK'S EQUATION

In 1900, the German physicist Max Planck was studying black-body radiation and proposed a controversial solution to the ultraviolet catastrophe.

Planck assumed that light was emitted as discrete packets. He called the discrete packets of energy 'quanta', and developed an equation for the energy, E, of each **quantum**.

$$E = hf = \frac{hc}{\lambda}$$

where

E is the energy of a quantum of light (J)
f is the frequency of the electromagnetic radiation (Hz)
h is the constant 6.626×10^{-34} J s, now known as Planck's constant
c is the speed of light 3×10^{8} m s
λ is the wavelength of the light (m).

The term **photon** is now used to describe a single quantum of light. Since electromagnetic radiation is more commonly described according to its wavelength, scientists often combine Planck's equation with the wave equation for light, $c = f\lambda$, as seen in the second half of the equation.

THE ELECTRON VOLT

The **electron volt** was introduced in Chapter 3 of *Pearson Physics Queensland Units 1 & 2*. Recall that an electron volt is the amount of energy an electron gains when it moves through a potential difference of 1V. Since the charge on an electron is -1.6×10^{-19} C, then:

$$\begin{aligned} 1\,\text{eV} &= 1e \times 1\text{V} \\ &= 1.60 \times 10^{-19}\,\text{C} \times 1\,\text{J}\,\text{C}^{-1} \\ &= 1.60 \times 10^{-19}\,\text{J} \end{aligned}$$

Here is a simple way to convert between the units for energy:

To convert a value expressed in J into eV, divide it by 1.60×10^{-19} J eV^{-1}.
To convert a value expressed in eV into J, multiply it by 1.60×10^{-19} J eV^{-1}.

Worked example 9.3.1

USING PLANCK'S EQUATION

Calculate the energy of a quantum (a single photon) of ultraviolet light that has a frequency of 2.00×10^{15} Hz. Give the answer in joules and electron volts.	
Thinking	**Working**
Recall Planck's equation.	$E = hf$
Substitute in the appropriate values to solve in joules.	$E = \left(6.626 \times 10^{-34}\right) \times \left(2.00 \times 10^{15}\right)$ $= 1.33 \times 10^{-18}$ J
Convert the energy to electron volts.	$= \dfrac{1.33 \times 10^{-18}\,\text{J}}{1.60 \times 10^{-19}\,\text{J eV}^{-1}}$ $= 8.28$ eV

➤ Try yourself 9.3.1

USING PLANCK'S EQUATION

Calculate the energy of a quantum of infrared radiation that has a frequency of 3.6×10^{14} Hz.

Give the answer in joules and electron volts.

FURTHER EVIDENCE OF LIGHT AS A PARTICLE

Scientists noticed that when some types of electromagnetic radiation are incident on a piece of metal, the metal becomes positively charged. This positive charge is due to electrons being ejected from the surface of the metal. The electrons became known as **photoelectrons** because they were released due to light or other forms of electromagnetic radiation. The phenomenon is known as the **photoelectric effect**.

A common apparatus used to observe the photoelectric effect consists of a clean metal surface (the cathode) illuminated with light from an external source. If the light causes photoelectrons to be emitted, they are detected at the anode. The flow of electrons is called the **photocurrent** and is registered by a sensitive ammeter.

The circuit (Figure 9.3.1) includes a variable voltage supply that can be used to make the cathode negative (and the anode positive). When this is done, the photoelectrons will be repelled by the negative potential at the cathode and attracted to the positive potential at the anode. As a result, a maximum possible current will be measured. Alternatively, the voltage may be adjusted to make the cathode positive and the anode negative. This repels the photoelectrons and slows them down. As the anode voltage is increased, the photoelectrons are repelled more and more until the photocurrent drops to zero.

Using apparatus such as that shown in Figure 9.3.1, the German physicist Philipp Lenard made several surprising discoveries about the photoelectric effect. He was awarded the Nobel Prize in Physics in 1905 for his discoveries.

Lenard used a filter to vary the frequency of the incident light. He discovered that, for a particular cathode metal, there is a certain frequency below which no photoelectrons are observed. This is called the **threshold frequency**, f_0. For frequencies of light greater than the threshold frequency (i.e. $f > f_0$), photoelectrons will be collected at the anode and registered as a photocurrent. For frequencies below the threshold frequency (i.e. $f < f_0$), no photoelectrons will be released and so no current flows.

Lenard also discovered that, for light that has a frequency greater than the threshold frequency (that is, $f > f_0$), the rate at which the photoelectrons are produced varies in proportion with the intensity (brightness) of the incident light, as shown in Figure 9.3.2.

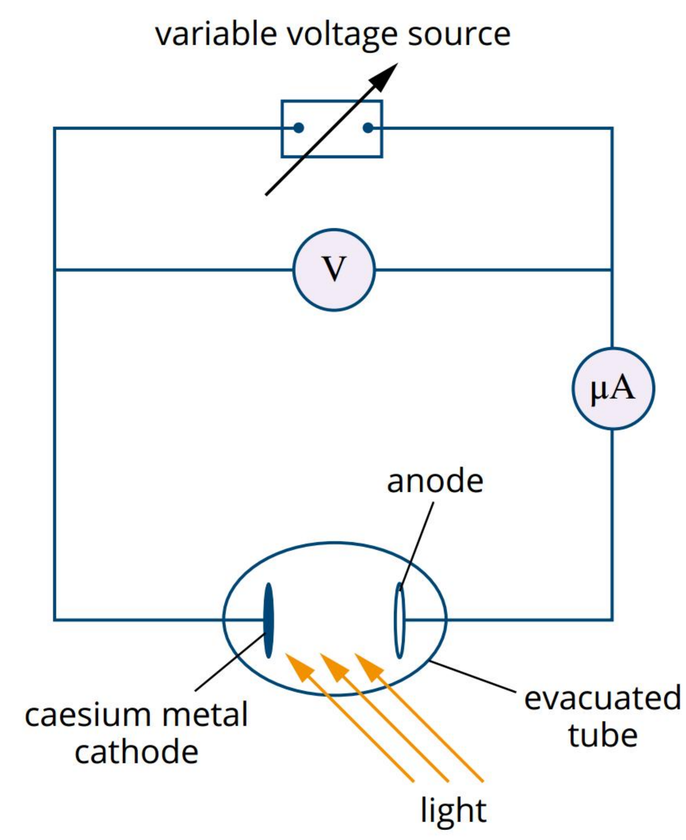


FIGURE 9.3.1 Circuit diagram of an experimental investigation of the photoelectric effect

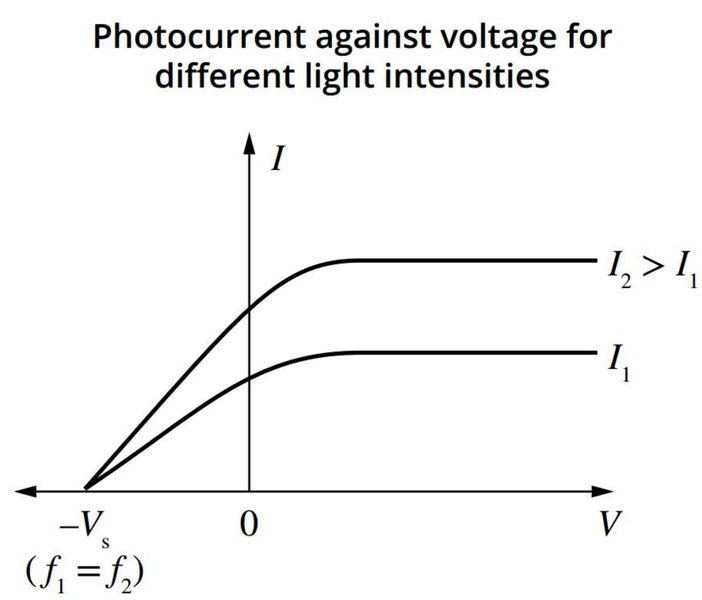


FIGURE 9.3.2 Photocurrent (I) plotted as a function of the voltage (V) applied between the cathode and the anode for different light intensities. For brighter light ($I_2 > I_1$) of the same frequency ($f_1 = f_2$), there is a higher photocurrent, but the same stopping voltage, V_s.

This graph shows several important properties of the photoelectric effect:

- When the light intensity increases, the photocurrent increases.
- When the applied voltage is positive, photoelectrons are attracted to the collector electrode (anode). A small positive voltage is enough to ensure that every available photoelectron is collected. The current therefore reaches a maximum value and remains there even if the voltage is increased.
- When the applied voltage is negative, photoelectrons are attracted back towards the illuminated cathode and repelled by the collector electrode (anode), and the photocurrent is reduced. The photocurrent is reduced because fewer and fewer photoelectrons have the energy to overcome the opposing electric potential. There is a voltage, V_s for which no photoelectrons reach the collector. This is known as the **stopping voltage**. For a particular frequency of light on a particular metal, this stopping voltage is a constant.

Recall from earlier studies of electricity that the work done on a charge (by an applied voltage) is given by $W = qV$. In this case, the voltage used is designated the stopping voltage, V_s, and the charge is equal to the magnitude of the charge on an electron, q_e, 1.60×10^{-19} C. Hence the work done on the electron is given by $W = q_e V_s$. Since the stopping voltage is large enough to stop even the fastest-moving electrons from reaching the anode, this expression gives the value of the maximum possible kinetic energy of the emitted photoelectrons. For example, for a stopping voltage of 2.5 V, the maximum kinetic energy of any photoelectron is 2.5 eV.

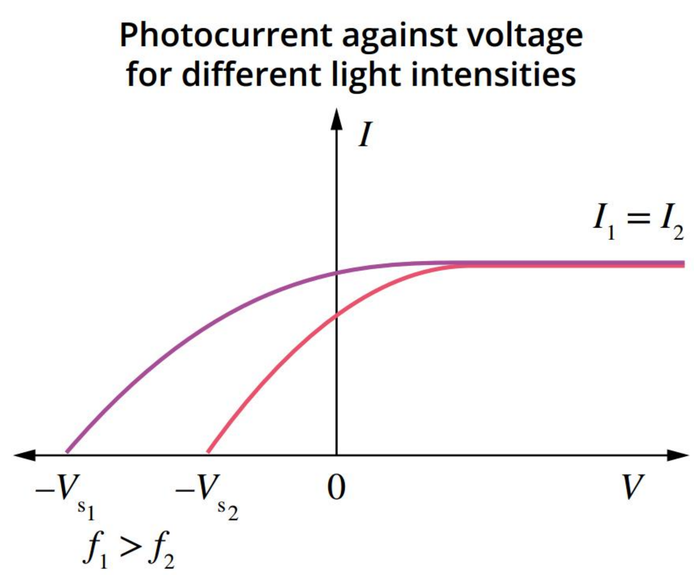


FIGURE 9.3.3 Photocurrent (I) plotted as a function of the voltage (V) applied between the cathode and the anode for different frequencies ($f_1 > f_2$) of incident light with the same intensity ($I_1 = I_2$). Both frequencies produce the same maximum photocurrent; however, light with the higher frequency requires a larger stopping voltage.

When light sources of the same intensity but different frequencies are used, they produce the same maximum current. However, the higher-frequency light has a higher stopping voltage (Figure 9.3.3).

Finally, if the incident light has a frequency above the threshold frequency of the cathode material, photoelectrons are found to be emitted without any appreciable time delay. This fact holds true regardless of the intensity of the light.

When illuminated with light above the threshold frequency, some photoelectrons are emitted from the first layer of atoms on the surface of the metal and have the maximum kinetic energy possible. Other photoelectrons come from deeper inside the metal and lose some of their kinetic energy due to collisions on their way to the surface. Hence, the emitted photoelectrons have a range of kinetic energies from the maximum value down.

EXPLAINING THE PHOTOELECTRIC EFFECT

The characteristics of the photoelectric effect could not be explained using a wave model of light. According to the wave model, the frequency of light should be irrelevant as to whether photoelectrons are ejected. Since a wave is a form of continuous energy transfer, it would be expected that even low-frequency light should transfer enough energy to emit photoelectrons if left incident on the metal for long enough. Similarly, the wave model predicts that there should be a time delay between the light striking the metal and photoelectrons being emitted, as the energy from the wave builds up in the metal over time.

In 1905, Albert Einstein proposed a solution to this problem. Einstein drew on Planck's earlier work by assuming that light exists as particles, or photons (like Planck's 'quanta'), each with an energy of $E = hf$. This assumption made the properties of the photoelectric effect relatively easy to explain.

Einstein's work was a significant extension of Planck's ideas. Although Planck had assumed that light was being emitted in quantised packets, he never questioned the assumption that light was fundamentally a wave phenomenon.

Einstein's work went further, challenging scientists' understanding of the nature of light itself.

Einstein and the photoelectric effect

Einstein identified that, for a particular metal, the amount of energy required to eject a photoelectron is a constant value that depends on the strength of the bonding within the metal. This energy was called the **work function**, W, of the metal. For

example, the work function of lead is 4.25 eV, which means that 4.25 eV of energy is needed to release a single electron from the surface of a piece of lead. Table 9.3.1 shows the work functions of some common metals.

According to Einstein's model, shining light on the surface of a piece of metal is equivalent to bombarding it with photons. When a photon strikes the metal, it can transfer its energy to an electron. That is, a single photon can interact with a single electron, transferring all of its energy at once to the electron. What happens next depends on whether or not the photon contains enough energy to overcome the work function.

If the energy of the photon is less than the work function, then photoelectrons will not be released as the electrons will not gain enough energy to let them break free of the metal atoms. For example, the photons of violet light ($f = 7.50 \times 10^{14}$ Hz) each contain 3.11 eV of energy.

$$\begin{aligned} E &= hf \\ &= (6.626 \times 10^{-34}) \times (7.50 \times 10^{14}) \\ &= 4.97 \times 10^{-19}\,\text{J} \\ &= \frac{4.97 \times 10^{-19}}{1.60 \times 10^{-19}} \\ &= 3.11\,\text{eV} \end{aligned}$$

This means that violet light shining on lead would not release photoelectrons since the energy of each photon, 3.11 eV, is less than the work function of lead, 4.25 eV.

However, ultraviolet photons of frequency 1.20×10^{15} Hz each contain 4.97 eV of energy.

$$\begin{aligned} E &= hf \\ &= (6.626 \times 10^{-34}) \times (1.20 \times 10^{15}) \\ &= 7.95 \times 10^{-19}\,\text{J} \\ &= \frac{7.95 \times 10^{-19}}{1.60 \times 10^{-19}} \\ &= 4.97\,\text{eV} \end{aligned}$$

Therefore, ultraviolet light of this frequency would release photoelectrons from the lead since the energy of each photon, 4.97 eV, is greater than the work function of lead, 4.25 eV.

Each metal has a threshold frequency; this is the frequency at which the photons have an energy equal to the work function of the metal. The work function is given by:

$W = hf_0$
where
W is the work function (J)
h is Planck's constant
f_0 is the threshold frequency for that metal (Hz).

TABLE 9.3.1 The work functions of some common metals

Metal	Work function (eV)
potassium	2.29
calcium	2.87
zinc	3.63–4.9
lead	4.25
silver	4.26–4.74
gallium	4.32
tin	4.42
mercury	4.475
iron	4.67–4.81
gold	5.10–5.47

Worked example 9.3.2

CALCULATING THE WORK FUNCTION OF A METAL

Calculate the work function (in J and eV) for aluminium, which has a threshold frequency of 9.8×10^{14} Hz.

Thinking	Working
Recall the formula for work function.	$W = hf_0$
Substitute the threshold frequency of the metal into this equation.	$W = (6.626 \times 10^{-34}) \times (9.8 \times 10^{14})$ $= 6.5 \times 10^{-19}\,\text{J}$
Convert this energy from J to eV.	$W = \frac{6.5 \times 10^{-19}}{1.60 \times 10^{-19}}$ $= 4.1\,\text{eV}$

➤ Try yourself 9.3.2

CALCULATING THE WORK FUNCTION OF A METAL

Calculate the work function (in J and eV) for gold, which has a threshold frequency of 1.2×10^{15} Hz.

THE KINETIC ENERGY OF PHOTOELECTRONS

If the photon energy exceeds the metal's work function, a photoelectron is emitted. The excess energy beyond the work function is transformed into the kinetic energy of the photoelectron.

Einstein described this relationship with his photoelectric equation:

$E_k = hf - W$

where

E_k is the maximum kinetic energy of an emitted photoelectron (J)

h is Planck's constant

f is the frequency of the incident photon (Hz)

W is the work function of the metal (J).

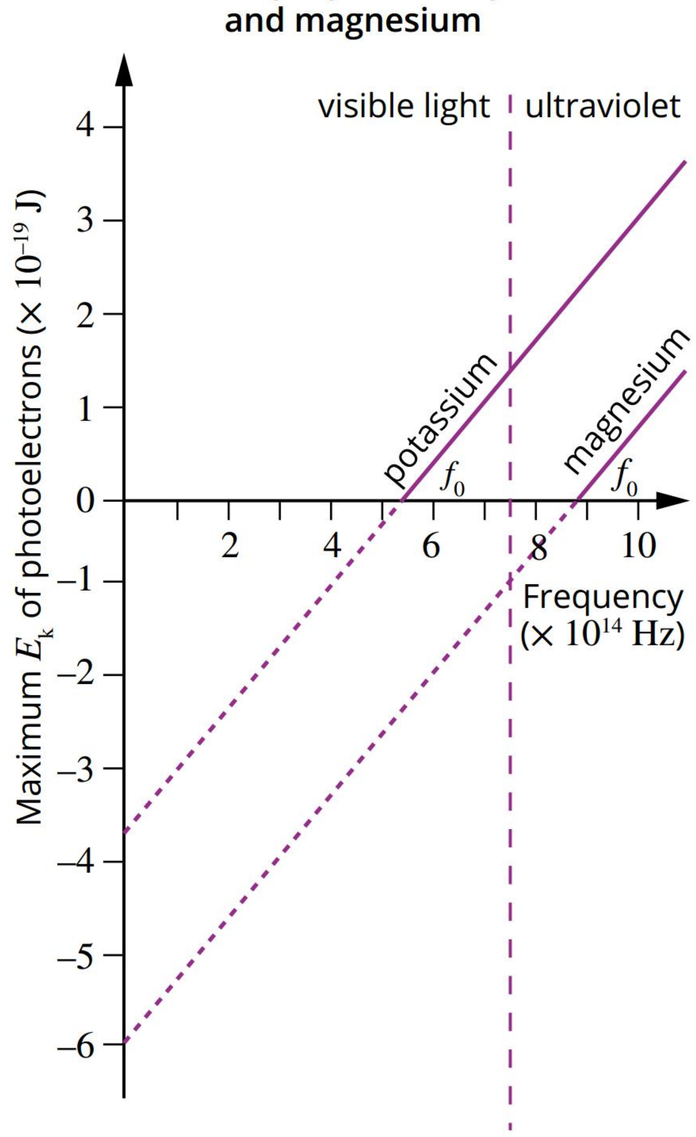


FIGURE 9.3.4 Magnesium has a high threshold frequency, which is in the ultraviolet region. The threshold frequency for potassium is in the visible region. The gradient of the graph for each metal is Planck's constant, h. The x-intercept gives the threshold frequency, f_0. The magnitude of the y-intercept gives the work function, W.

Graphing Einstein's equation results in a linear (straight line) graph like the one shown in Figure 9.3.4. Such a graph is useful because it clearly shows key information, such as the work function and threshold frequency for a particular metal.

Einstein's equation $E_k = hf - W$ can be compared with the equation of a straight line, $y = mx + c$. In making this comparison, extrapolating (extending) the graph back to the vertical axis will give the magnitude of the work function, W (Figure 9.3.4). The gradient of the graph is Planck's constant, h. From the graph it is also apparent how, as soon as the threshold frequency is exceeded, an electron can be ejected and escape with some kinetic energy. The greater the frequency of the light, the greater the kinetic energy of the photoelectron. At the threshold frequency, electrons are no longer bound to the metal, but they have no kinetic energy.

The y-intercept (i.e. negative of the work function), and x-intercept (threshold frequency) of the graph change when different metals are measured, but the gradient is always the same (Planck's constant).

Worked example 9.3.3

CALCULATING THE KINETIC ENERGY OF PHOTOELECTRONS

Calculate the kinetic energy (in J and eV) of the photoelectrons emitted from lead by ultraviolet light with a frequency of 1.2×10^{15} Hz. The work function of lead is 4.25 eV.

Thinking	Working
Convert work function from eV to J.	$W = 4.25 \times (1.6 \times 10^{-19})$ $= 6.80 \times 10^{-19}$ J
Recall Einstein's photoelectric equation.	$E_k = hf - W$
Substitute values into this equation.	$E_k = (6.626 \times 10^{-34}) \times (1.2 \times 10^{15}) - 6.80 \times 10^{-19}$ $= 7.95 \times 10^{-19} - 6.80 \times 10^{-19}$ $= 1.15 \times 10^{-19}$ $= 1.2 \times 10^{-19}$ J
Convert E_K from J to eV.	$E_k = \frac{1.15 \times 10^{-19}}{1.6 \times 10^{-19}}$ $E_k = 0.72$ eV

➤ Try yourself 9.3.3

CALCULATING THE KINETIC ENERGY OF PHOTOELECTRONS

Calculate the maximum possible kinetic energy (in J and eV) of the photoelectrons emitted from lead by ultraviolet light with a frequency of 1.5×10^{15} Hz. The work function of lead is 4.25 eV.

Worked example 9.3.4

INTERPRETING PHOTOELECTRIC EFFECT DATA

Using Figure 9.3.4, determine the work function (in J and eV) and threshold frequency of potassium.	
Thinking	**Working**
Recall the *y*-intercept of a kinetic energy vs frequency graph is the negative of the work function.	*y*-intercept is -3.7×10^{-19} J $W = 3.7 \times 10^{-19}$ J
Convert the work function from J to eV	$W = \frac{3.7 \times 10^{-19}}{1.6 \times 10^{-19}}$ $= 2.3$ eV
Recall that the threshold frequency is given by the *x*-intercept of the graph.	$f_0 = 5.5 \times 10^{14}$ Hz

➤ Try yourself 9.3.4

INTERPRETING PHOTOELECTRIC EFFECT DATA

Using Figure 9.3.4, determine the work function (in J and eV) and the threshold frequency of magnesium.

WAVE–PARTICLE DUALITY

In many ways, the wave and particle models for light seem fundamentally incompatible. Waves are continuous and are described in terms of wavelength and frequency. Particles are discrete and are described by physical dimensions such as mass and radius.

To understand how these two sets of ideas can be used together, it is important to remember that scientists describe the universe using models. Models are analogies that are used to illustrate certain aspects of reality that might not be immediately apparent.

Physicists have come to accept that light is not easily compared to any other classical phenomenon. In some situations, light has similar properties to a wave; in other situations, light behaves more like a particle. This understanding is called **wave–particle duality** (Figure 9.3.5). Although this may seem somewhat paradoxical and counterintuitive, in the century since Einstein did his work establishing quantum theory, many experiments have supported this duality and no scientist has come up with a better explanation. Wave–particle duality is explored in more detail in Chapter 10.

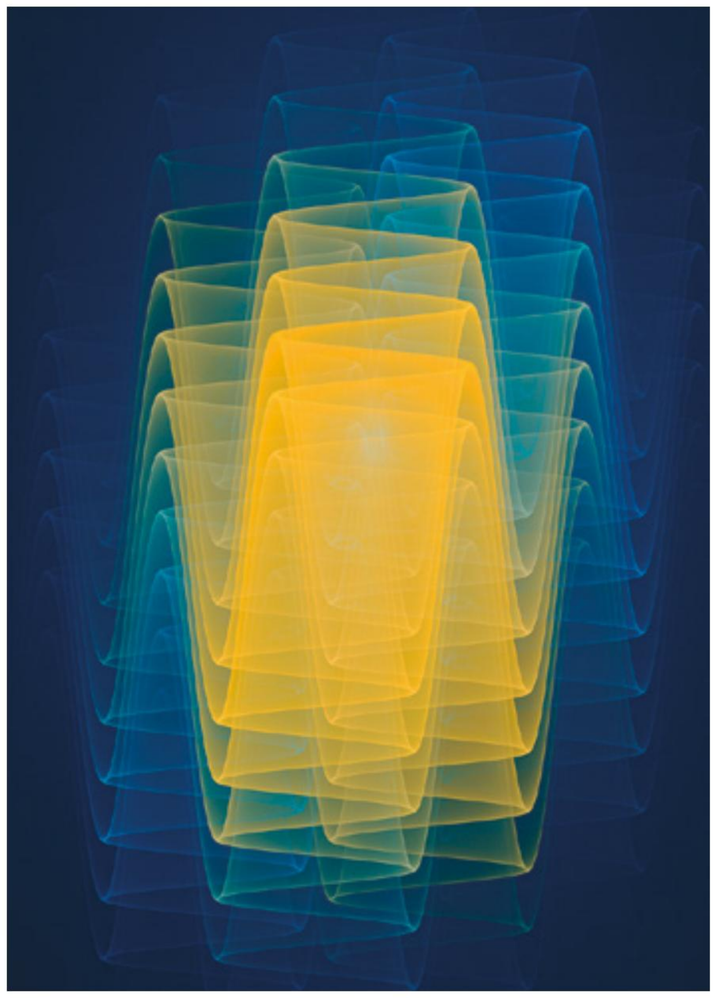


FIGURE 9.3.5 An artist's attempt to represent wave–particle duality

9.3 Review

SUMMARY

- At the atomic level, electromagnetic radiation is emitted or absorbed in discrete packets or quanta called photons.
- The energy of a photon is proportional to its frequency or inversely proportional to its wavelength:

$$E = hf = \frac{hc}{\lambda}$$

- The electron volt is an alternative (non-SI) unit of energy: $1\,\text{eV} = 1.60 \times 10^{-19}\,\text{J}$.
- The photoelectric effect is the emission of photoelectrons from a clean metal surface due to incident light with frequency, f, that is greater than the threshold frequency, f_0, for that particular metal.
  - If $f < f_0$, no electrons are released.
  - If $f > f_0$, the rate of electron release (the photocurrent) is proportional to the intensity of the light and occurs without any time delay.
- Increasing the forward voltage does not alter the rate of electron release (i.e. the photocurrent).
- The maximum kinetic energy of an emitted photoelectron can be calculated using $E_k = hf - W$.
- The work function, W, for the metal is given by $W = hf_0$, and is different for each metal. If the frequency of the incident light is greater than the threshold frequency, then a photoelectron will be ejected with some kinetic energy up to a maximum value.
- A graph of E_k versus frequency will have a gradient equal to Planck's constant, h, and a y-intercept equal to the negative work function, W.
- The wave approach to light could not explain various features of the photoelectric effect.
- Einstein used Planck's concept of a photon to explain the photoelectric effect, stating that each electron release was due to an interaction with only one photon.
- The photon model of light explained the existence of a threshold frequency for each metal, the absence of a time delay for the photocurrent even for weak light sources and why brighter light resulted in a higher photocurrent.

KEY QUESTIONS

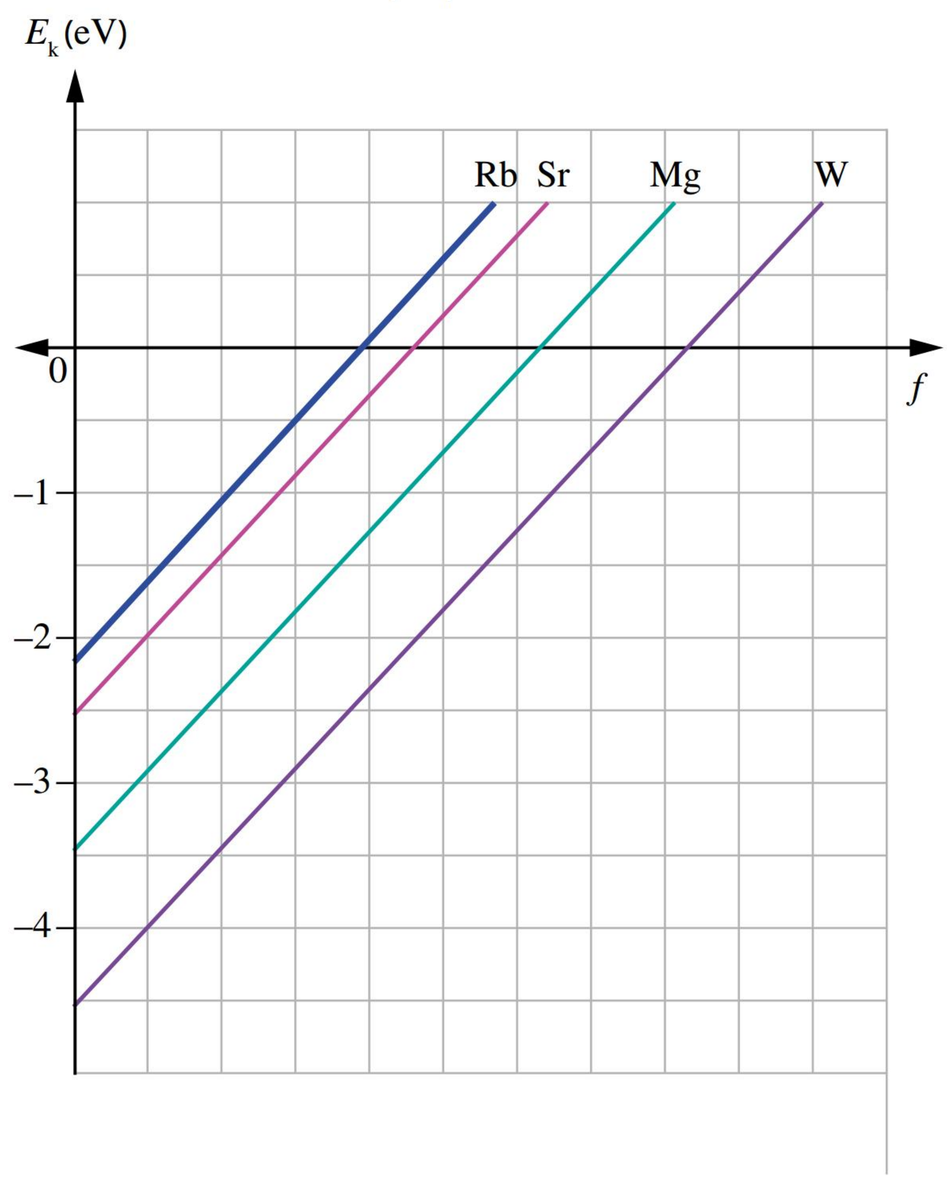
Describe

1. Describe why the electron volt (eV), a non-SI unit, is used for the energy of photons rather than the SI unit the joule (J).
2. Describe what is meant by the term photon.
3. Describe Planck's equation.
4. Describe the photoelectric effect.
5. Explain what the threshold frequency corresponds to.

Apply

6. Explain why a piece of metal might become positively charged when light shines on its surface.
7. From the graph, determine the value of the work function for each of the metals.

Photoelectric properties of four metals



Analyse

8 Calculate the energy, in J, of a gamma ray photon with a frequency of 2.42×10^{27} Hz.

9 Calculate the energy of a photon of yellow light with a wavelength of 523 nm. Express your answer in:

a joules

b electron volts.

10 A photon of blue light has an energy of 4.86×10^{-19} J; determine the wavelength of the light.

11 Calculate the energies (in joules) of the following wavelengths of light:

	Colour	Wavelength (nm)	Energy (J)
a	red	656	
b	yellow	589	
c	blue	486	
d	violet	397	

12 Calculate the work functions (in electron volts) of the following metals:

	Metal	Threshold frequency (Hz)	Work function (eV)
a	aluminium	9.85×10^{14}	
b	caesium	4.23×10^{14}	
c	platinum	1.5×10^{15}	

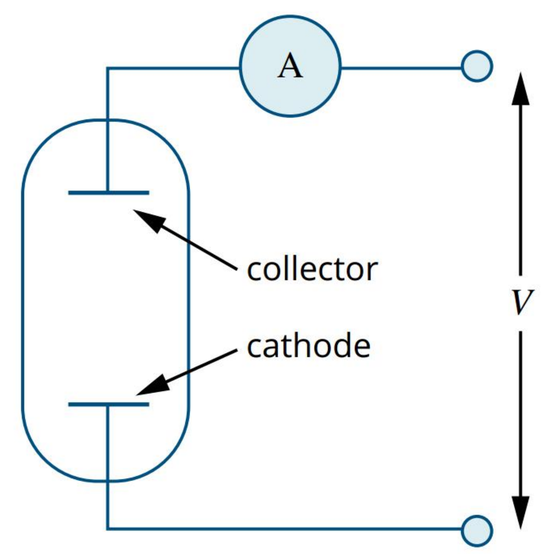
13 In an experiment on the photoelectric effect, different frequencies of light were shone on a piece of magnesium with a work function of 3.66 eV. Calculate the lowest frequency of incident light that would produce photoelectrons from a sample of magnesium.

14 Blue light with a wavelength of 475 nm is shone on a piece of sodium with a work function of 2.36 eV. Calculate the maximum kinetic energy, in electron volts, of the emitted photoelectrons.

15 Yellow–green light of wavelength 500.0 nm shines on a metal whose stopping voltage is found to be 0.800 V. Calculate the work function of the metal in electron volts.

16 Iron has a work function 4.7 eV. Light with a frequency of 2.45×10^{15} Hz is shone onto the surface. Calculate the maximum kinetic energy of the emitted photoelectrons.

17 The cathode of a particular photocell, shown below, is coated with rubidium. Incident light of varying frequencies is directed onto the cathode and the maximum kinetic energy of the photoelectrons is logged. The results are summarised in the following table:



Frequency ($\times 10^{14}$ Hz)	E_K (eV)
5.20	0.080
5.40	0.163
5.60	0.246
5.80	0.328
6.00	0.411
6.20	0.494

a Plot the results from the table on a graph.

b Calculate the gradient of your graph.

c Determine the threshold frequency of rubidium from the graph.

d Determine whether red light of wavelength 680 nm causes photoelectrons to be emitted from the rubidium surface. Justify your answer.

Chapter review

09

KEY TERMS

black body
coherent
constructive interference
destructive interference
double-slit experiment
electron volt
infrared
interference
photocurrent
photoelectric effect
photoelectron
photon
quantum
stopping voltage
threshold frequency
ultraviolet
visible light
wave
wave–particle duality
work function

KEY QUESTIONS

Describe

1 Identify why the wave model of light cannot satisfactorily explain the photoelectric effect, by selecting the best option below.

A The non-existence of interference patterns shows that light is not a wave.

B Energy in waves is not sufficient to eject photoelectrons from the surface of a metal.

C The energy in waves all arrives at the same moment, while multiple particles can all provide their energy to a single electron.

D Waves provide continuous energy that would accumulate over time to release photoelectrons even if its frequency was lower than the threshold frequency.

2 Describe the double-slit experiment and explain why it is considered evidence for the wave theory of light.

3 Describe the work function of a metal and what effect it has on a photoelectron.

Apply

4 Which of these numbers represents Planck's constant expressed in electron volt seconds (eV s)?

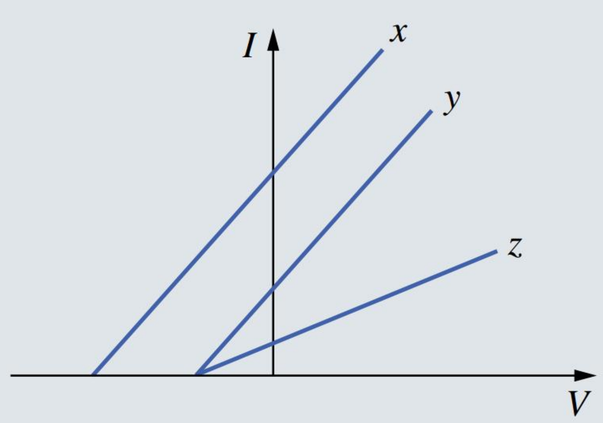
A 4.25

B 1.6×10^{-19}

C 6.626×10^{-34}

D 4.14×10^{-15}

5 In a photoelectric effect experiment, three beams of light x, y and z are incident on a metal. The graph below shows the current and potential difference recorded in the circuit during the experiment for the three beams.



Which statement about the three beams is correct?

A *x* and *y* have the same frequency.

B *x* and *z* have the same intensity.

C *y* and *z* have the same frequency.

D *y* and *z* have same intensity.

6 Identify which statement is true about the photoelectric effect for a particular metal surface.

A The stopping voltage depends on the intensity of the light.

B The stopping voltage depends on the frequency of the light.

C The threshold frequency depends on the stopping voltage.

D The work function depends on the intensity of the light.

Analyse

7 An AM radio station broadcasts at a frequency of 612 kHz. Calculate the wavelength of the waves broadcast if the speed of light is $3 \times 10^8\,\mathrm{m\,s^{-1}}$.

8 Calculate the energy (in J) of a quantum of infrared radiation that has a frequency of 3.6×10^{14} Hz.

9 Calculate the energy of a photon of red light with a wavelength of 640 nm.

10 A photon has an energy of 4.1 eV, calculate the photon's frequency.

11 Wien's displacement law can be written as $\lambda_{max} T = 2.898 \times 10^{-3}\,\mathrm{m\,K}$ where λ is in m and the temperature is in K.

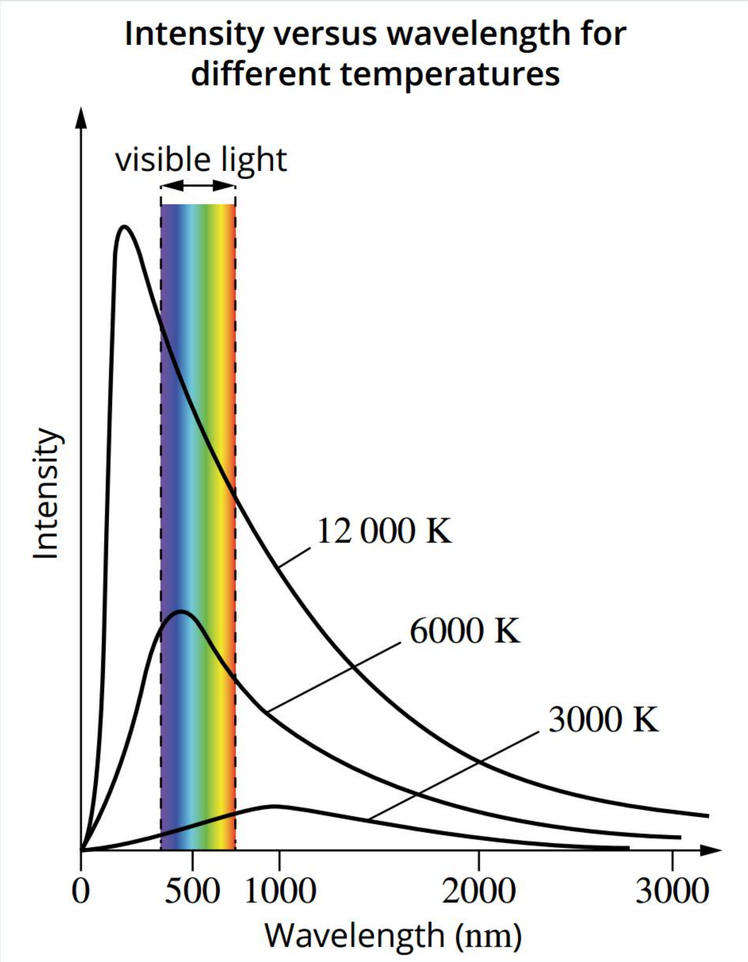
a Calculate the peak radiation wavelength for Earth at 290 K.

b Calculate the temperature of a sample of molten (liquid) iron glowing hot in a furnace that radiates at 414 nm.

12 A metal filament is heated as a current passes through it. Initially it glows a dull red. As the current is increased, the red becomes brighter, the wire then glows yellow and eventually glows bright white.

a Analyse the following graph and explain the reasons for the colour changes of the metal filament at each stage.

b Describe and explain the colour of the filament if the current was increased further.



13 Arj conducts an experiment to verify the value of the constant in Wien's displacement law by measuring the peak wavelength produced by a heating element and its temperature. He produced the following data:

Temperature (K)	Peak wavelength ($\times 10^{-6}$ m)
700	4.2
760	3.8
815	3.5
870	3.2
925	3.1

Use two different data points to calculate an average value of the constant in Wien's displacement law.

14 In the initial condition, the temperature of a black body is given by T and the peak wavelength emitted is given by λ. If the temperature increases by 25%, calculate the new peak wavelength.

15 Photoelectrons are emitted from a metal surface with a maximum kinetic energy of 3.0 eV. The incident light has a frequency of 1.15×10^{15} Hz. Calculate the work function for this metal.

Interpret

16 Demonstrate that the photoelectric effect could be used by a self-driving car to be able to tell when traffic lights change. Select one of the metals in Table 9.3.1 on page 247 that will emit photoelectrons when a blue light ($\lambda = 400$ nm) is shining on it but not when a red light ($\lambda = 800$ nm) is shining on it. (There is still work to be done on being able to detect green lights.)

17 When conducting a photoelectric effect experiment, Maree correctly observes that the energy of emitted electrons depends only on the frequency of the incident light and is independent of the intensity.

a Explain how the particle model accounts for this observation.

b Explain why the wave model cannot account for this observation.

c Make three statements about how the particle (photon) model of light is supported by features of the photoelectric effect and discuss the implications for the wave model of light in each case.

Maree obtains the following data.

Wavelength (nm)	Maximum kinetic energy (eV)
350	1.40
400	0.91
450	0.60
500	0.25

d Plot a graph of the energy as a function of frequency.

e Analyse the graph to find a value of Planck's constant and the work function of the metal.

f If there is an uncertainty of ±0.1 in the analysis of the work function, use the table below to find which metal was used in this experiment.

Metal	Work function
aluminium	4.08
carbon	4.80
copper	4.70
potassium	2.30
caesium	2.10

18 Re-radiated energy from Earth is mostly in the infra-red region. Greenhouse gases also absorb and re-emit infra-red radiation. Draw a conclusion about the consequences this might have for the global temperatures.

Data analysis

DATA SET 1

The information below applies to Questions **1–4**.

An experiment was conducted to determine the work function of a Cesium–Antimony alloy. Different frequencies of light were shone on the alloy as a cathode within a circuit. The voltage to stop the photocurrent was recorded for each frequency. The stopping voltage was converted to an E_K value in joules and is presented in Figure 1 below. A trend line has been fitted to the data.

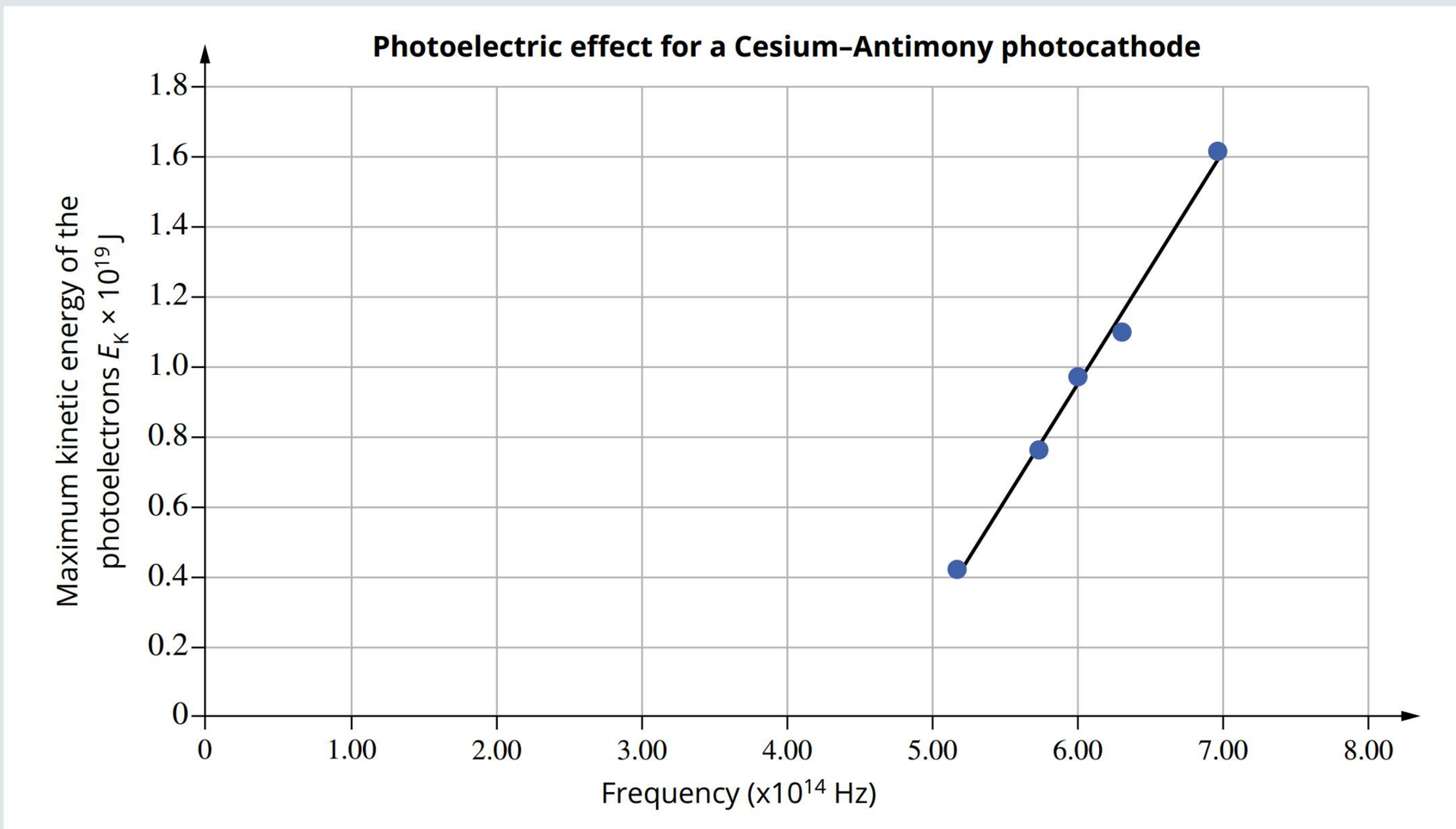


FIGURE 1 Photoelectric effect for a cesium–antimony photocathode

Question 1 (3 marks)

Calculate the equation for the trend line.

Question 2 (1 mark)

Determine the work function of this metal.

Question 3 (1 mark)

Identify the value for Planck's constant determined in the experiment.

Question 4 (2 marks)

Determine the threshold frequency for this metal.

CHAPTER 10

The atom

The atom is one of the basic building blocks of all matter. Humans have developed models of the atom from as early as 400 BCE, when the Greek philosopher Democritus suggested that everything was made up of tiny, indivisible particles. Scientists have refined models of the atom over millennia to better explain their observations of the world. In the early 1900s, ground-breaking work by Ernest Rutherford and his students led to a new understanding of the atom, including the extraordinary idea that most of the atom is empty space. Problems with Rutherford's description of the atom led to a new explanation by Niels Bohr, who explained observed phenomena such as emission and absorption spectra. Further work to improve on Bohr's model of the atom by physicists such as Louis de Broglie led to the idea that, if light could be thought of as particles, then matter could also be thought of as waves. The strange world of the quantum mechanical model of the atom will be explored in this chapter.

Syllabus subject matter

QUANTUM THEORY

- Compare the different models of the atom proposed by Rutherford and Bohr. **10.1, 10.2**
- Explain how Bohr's model of the hydrogen atom integrates light quanta and atomic energy states to explain the specific wavelengths in the hydrogen line spectrum. **10.2**
- Solve problems involving the line spectra of simple atoms using atomic energy states or atomic energy level diagrams using $n\lambda = 2\pi r$, $mvr = \frac{nh}{2\pi}$ and $\frac{1}{\lambda} = R\left(\frac{1}{n_f^2} - \frac{1}{n_i^2}\right)$. **10.3, 10.4**
- Describe wave–particle duality of light by identifying evidence that supports the wave characteristics of light and evidence that supports the particle characteristics of light. **10.3**
- Solve problems involving black-body radiation and the photoelectric effect using $\lambda_{max} = \frac{b}{T}$, $E = hf = \frac{hc}{\lambda}$, $E_k = hf - W$, $W = hf_0$ and $\lambda = \frac{h}{p}$. **10.3**

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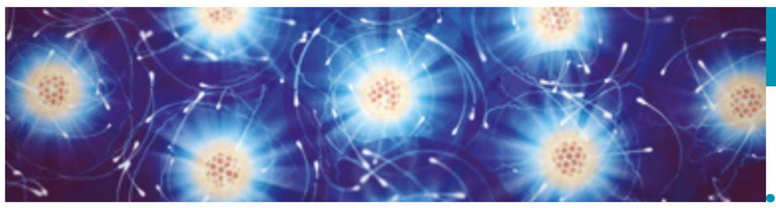
10.1 Rutherford's model



BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- describe Rutherford's model of the atom, including its limitations.

In Unit 1 of *Pearson Physics Queensland Units 1 & 2*, you may have investigated an early model of the atom: Thomson's plum pudding model. This module will illustrate Rutherford's model, which built on the work of Thomson. In 1909, the New Zealand physicist Ernest Rutherford and two of his students, Hans Geiger and Ernest Marsden, set out to test Thomson's plum pudding model of the atom. They wanted to probe this model using particles that Rutherford had discovered as Thomson's student: alpha particles.

GOLD FOIL SCATTERING EXPERIMENTS

The experiment involved a very thin piece of gold foil which was set up in a vacuum in the middle of a circular track that allowed a microscope sensor to move a full 360° around the foil. Directed at the gold foil was a source of alpha particles (helium nuclei), which are heavy, fast moving and positively charged.

The experiment was performed in a vacuum, so the alpha particles did not collide with particles other than the gold foil. The sensor was moved around the track and a fluorescent screen used to detect any alpha particles that were deflected or scattered from the foil (Figure 10.1.1).

As the accepted model of the atom (the plum pudding model) at the time consisted of evenly distributed, negatively charged electrons embedded in a 'pudding' of extended positive charge, the group expected the alpha particles to pass straight through the foil. This was because the alpha particles would be repelled from the positive pudding in all directions at once, and the net effect would be no deflection from the gold foil.

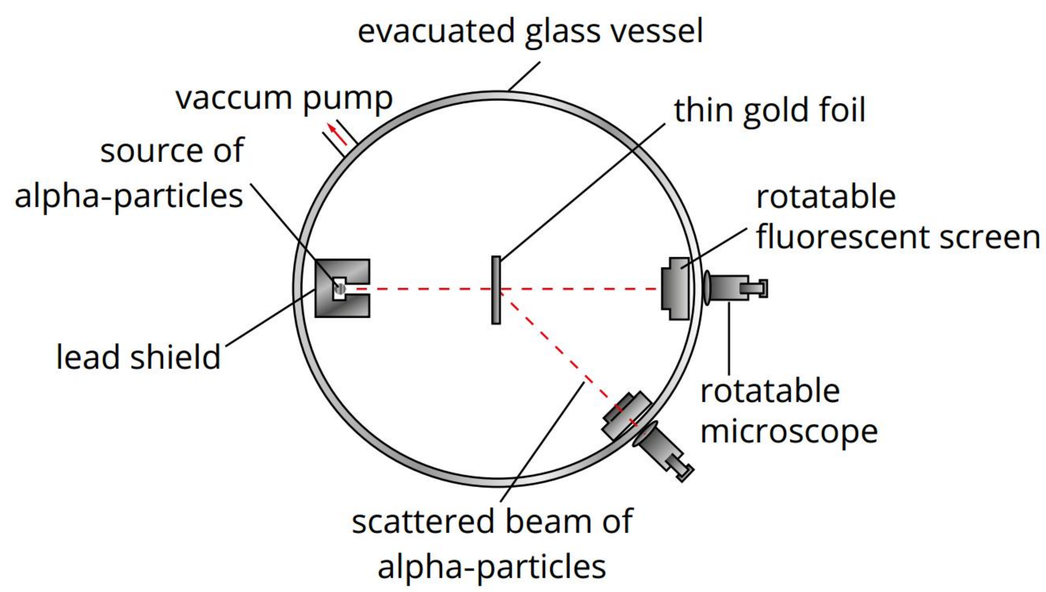


FIGURE 10.1.1 In Rutherford's scattering experiment, alpha particles are fired at thin gold foil (centre) and the scattering pattern is observed on the ring-shaped surface using the rotatable fluorescent screen and microscope.

Rutherford's results

Rutherford and his group expected the alpha particles to pass straight through the foil, and support the plum pudding model of the atom. They found that most of the alpha particles did pass straight through the gold foil; however, some were deflected at small angles, while others were deflected at large angles, and a few were even directed straight back at the source! Rutherford was later quoted as saying 'It was almost as incredible as if you fired a 15-inch shell at piece of tissue paper and it came back and hit you'.

These results led Rutherford to conclude that atoms contained a tiny, dense positively charged central nucleus. A comparison of the predicted results and experimental results is shown in Figure 10.1.2, in which the arrows represent the paths of the alpha particles and the red circle represents the newly discovered central region, or nucleus, of the gold atoms.

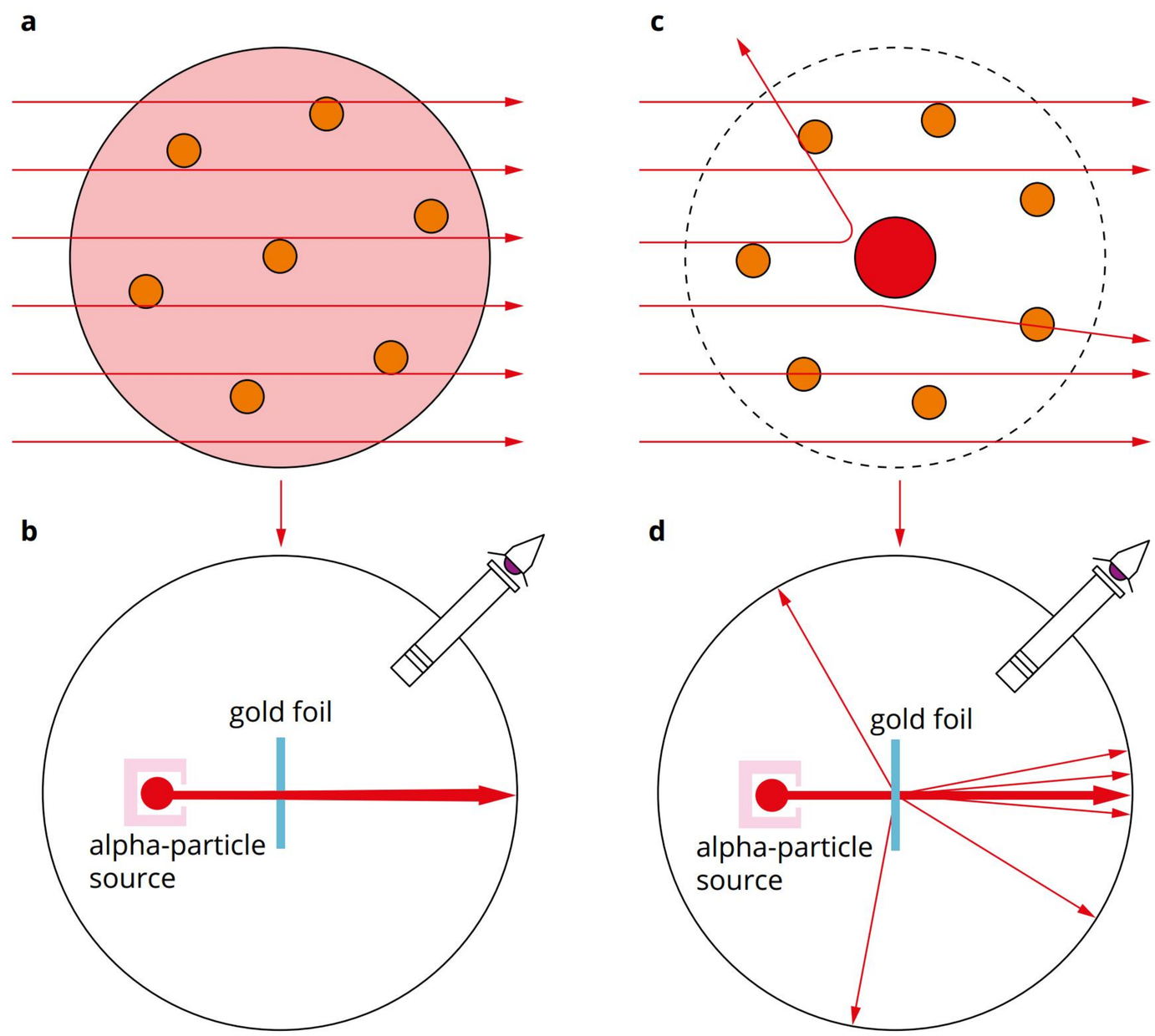


FIGURE 10.1.2 (a) In Thompson's atomic model the alpha particles would travel through the atom, affected only weakly by electrical forces, and (b) only low-angle scattering would be possible. (c) In Rutherford's atomic model most alpha particles travel through the atom, but some impact the nucleus and scatter, which is observed in the gold foil experiment (d).

RUTHERFORD'S ATOMIC MODEL

From the results of the gold foil experiments, and applying some mathematics, Rutherford concluded the following:

- The atom is mostly empty space with a tiny, very dense (about $10^{15}\,\text{kg}\,\text{m}^{-3}$), positively charged nucleus in the centre surrounded by even tinier, much lighter, negatively charged electrons. Note that at the time the proton and neutron were not known, so the nucleus was just considered to be a positively charged 'thing'.
- Nearly 100% of the atom's mass is contained in the nucleus.
- The number of electrons equals the number of positive charges in the nucleus.
- An atom's nucleus is in the order of 10^{-15} m in diameter.
- An atom is in the order of 10^{-10} m in diameter.
- The nucleus is 100 000 times smaller than the atom.

You can visualise this last statement by imagining the nucleus is the size of a tennis ball. At this scale, the electrons would occupy a region a few kilometres away from the tennis ball.

Problems with Rutherford's atomic model

Rutherford's model of the atom is the basis for the one now used, with some key refinements. It is important to understand that, although his work contributed to the basic picture of what an atom looks like, it did not explain all the observations.

Charged particles (such as electrons) radiate energy as they change velocity and are thus accelerating. Electrons orbiting a nucleus follow a circular path and so are constantly changing direction and so they are accelerating. This should cause the electrons to be constantly emitting energy. If the electrons are constantly losing energy in this process, they would eventually lose all their energy and spiral inwards towards the nucleus, imploding. This is not what is observed.

At about the same time that Rutherford was scattering alpha particles off gold foil, chemists found that excited atoms in their gaseous state emitted light. Not just any colour light but specific wavelengths of light called **emission spectra** (Figure 10.1.3a) that depended on the atom they were looking at. These emission spectra were like fingerprints for each element, that is, they were unique to each element. The hydrogen spectrum, in particular, was well studied by physicists. It will be covered in Module 10.4.

The problem with Rutherford's model is that it allowed the electrons to have *any* energy, and thus the light produced from them would be a **continuous spectrum** (Figure 10.1.3b) in which every wavelength of light is produced. This does not match the emission spectra observed in which only specific wavelengths are seen.

Bohr's model of the atom addresses these limitations and is discussed in Module 10.2.

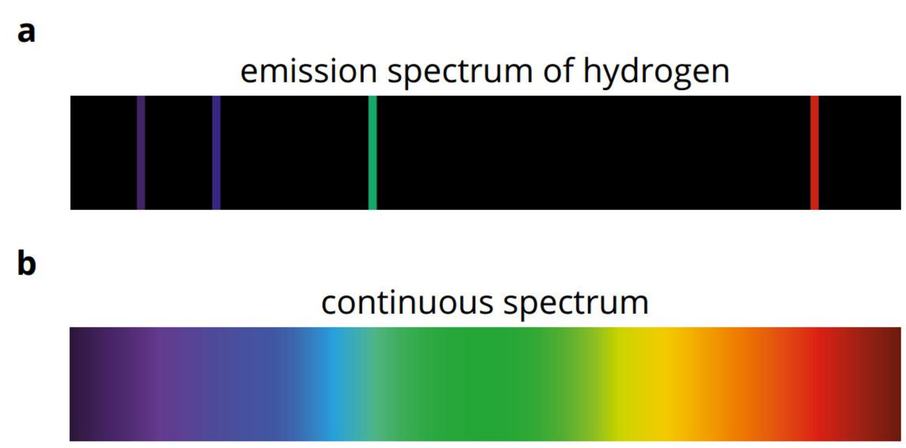


FIGURE 10.1.3 (a) The emission spectrum of hydrogen and (b) the continuous spectrum.

10.1 Review

SUMMARY

- Rutherford's gold foil experiment consisted of a beam of alpha particles striking a gold foil. Most alpha particles travelled straight through; a few alpha particles bounced off and scattered backwards.
- Rutherford's model of the atom contained the following ideas:
  - Most of the atom is empty space.
  - The atom is of the order of 10^{-10} m in size.
  - In the centre of the atom is the nucleus, which is 100 000 times smaller than the atom itself (of the order of 10^{-15} m in size).
  - The nucleus contains all the positive charge of the atom.
  - Surrounding the nucleus are the negatively charged electrons.
  - There are as many electrons as there are positive charges in the nucleus in a neutral atom.
- Rutherford's model does not explain:
  - why electrons don't spiral into the nucleus
  - why electrons don't emit energy continuously
  - the appearance of emission spectra where only discrete lines are observed.

KEY QUESTIONS

Describe

1 Describe the key features of Rutherford's model of the atom.

2 Describe the limitations of Rutherford's model of the atom.

Apply

3 Explain why an alpha particle would be repelled by a positive nucleus.

Analyse

4 If the nucleus was represented by a large marble (radius = 1 cm), calculate how big the whole atom would be.

5 Calculate the thickness of the gold foil used in Rutherford's experiment, given that the foil was 400 gold atoms thick and a gold atom is 300 pm across.

6 Deduce what conclusion Rutherford could have drawn if many more alpha particles had demonstrated large deflection angles.

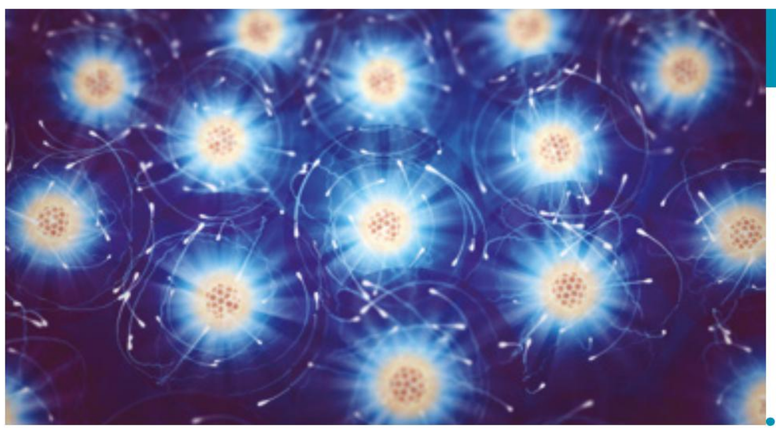
7 Thomson's plum pudding model consisted of a positive material and embedded in that was negative particles. Compare Thomson's and Rutherford's models of the atom.

8 A nucleus of a gold atom has a mass of 3.29×10^{-25} kg and a diameter of 14.0×10^{-15} m. Calculate the density of a gold nucleus.

9 To verify that the nucleus is 100 000 times smaller than the atom, determine what fraction of alpha particles are directly hitting the nucleus.

10 When Rutherford performed the gold foil experiment and proposed the existence of the nucleus, the proton and neutron had not yet been discovered (the proton in 1919, the neutron in 1932). If Rutherford had known about protons and neutrons, what conclusions might he have drawn because of the results of the gold foil experiment?

10.2 Bohr's model



BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- describe the Bohr model of the atom and compare Bohr's model to Rutherford's model
- explain how the Bohr model of the hydrogen atom integrates light quanta and atomic energy states to explain the specific wavelengths in the hydrogen line spectrum.

In 1913, Niels Bohr devised an improvement to Rutherford's model of the atom which addressed some of its problems and drew on the work of Planck and Einstein. Bohr's more sophisticated model focused on the electron **energy levels** in the atom. He was awarded a Nobel Prize in Physics in 1922 for this work.

FEATURES OF BOHR'S MODEL OF THE ATOM

Recall from Chapter 9 that Planck suggested that energy could be emitted in discrete packets called quanta. Bohr applied this idea to the energy levels of atoms to explain the specific wavelengths of the emission spectra. Bohr built on Rutherford's model by adding quantised electron energy levels based on Planck's ideas of quantised energy. These energy levels can be shown as several horizontal lines on what is known as an **energy level diagram**. Figure 10.2.1 shows the energy level diagram for sodium gas.

The energies of each level are negative in energy level diagrams, as this represents the energy required for an electron to gain before it is completely removed from the atom, or ionised.

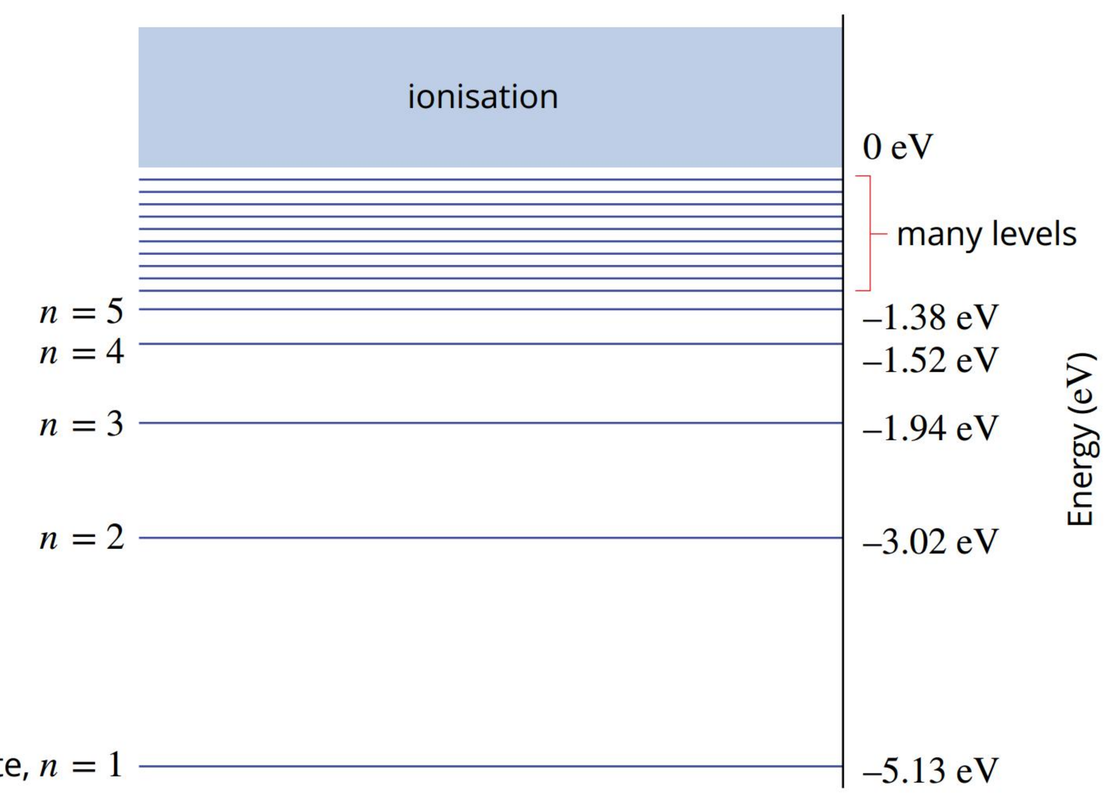


FIGURE 10.2.1 Energy levels in a sodium atom, $n = 1$ being the ground state. The highest level is where ionisation occurs and the electron escapes the atom.

Bohr's main ideas were as follows:

- The electron moves in a circular orbit around the nucleus of an atom.
- The force keeping the electron moving in a circle is the electrostatic force of attraction the positive nucleus attracts the negative electron.
- Several allowable orbits of different radii exist for each atom and are labelled $n = 1, 2, 3$, etc. The electron may occupy only these orbits.
- An electron ordinarily occupies the lowest energy orbit available.
- An electron does not radiate energy while it is in a stable orbit.
- An electron can jump to a higher energy level by absorbing some energy. The absorbed energy must be exactly equal to the difference between the electron's initial and final energy levels.

- Electromagnetic radiation is emitted by an excited atom when an electron falls from a higher energy level to a lower energy level. The energy of the emitted light will be exactly equal to the energy difference between the electron's initial and final levels.

These ideas are shown in Figure 10.2.2. In this example, the electron absorbs energy from light that strikes the atom. The energy absorbed is just the right amount for the electron to make the jump from its ground state to a higher level. In this diagram, the light is labelled as a photon.

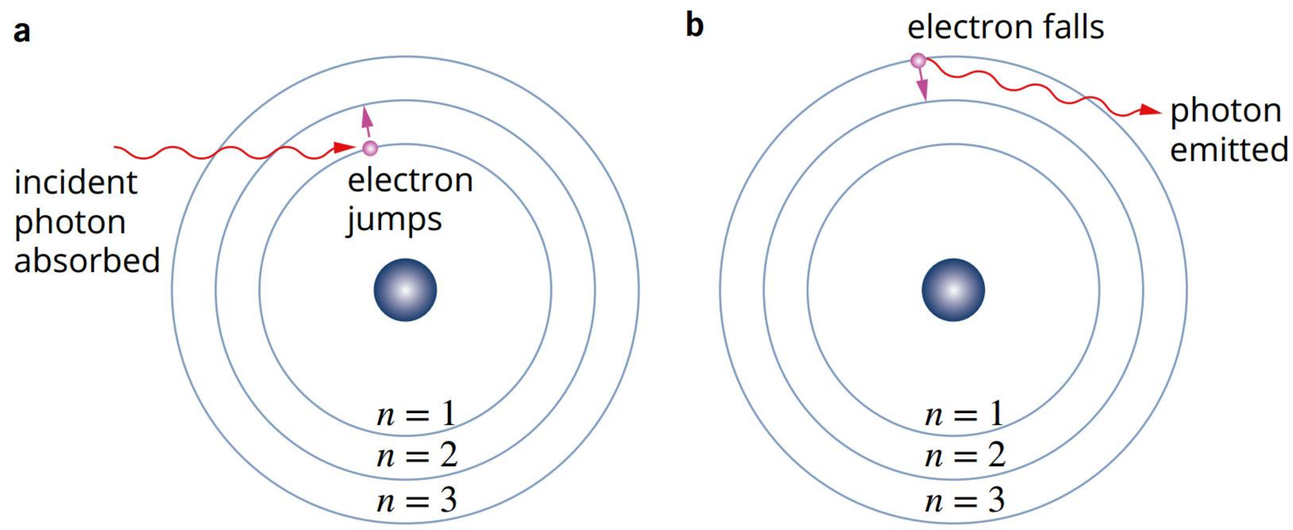


FIGURE 10.2.2 (a) If the incident photon (light) carries an amount of energy equal to the energy difference between two levels, the photon's energy can be absorbed, allowing the electron to jump to the higher level. The photon ceases to exist. (b) An atom will remain in an excited state for less than a millionth of a second. The electron will then fall to its ground state. The electron may fall in one step, or in several stages, emitting a photon or photons as it falls.

How Bohr's model improved on Rutherford's model

Recall from Module 10.1 that Rutherford's model did not explain three main observations:

- why electrons don't spiral into the nucleus
- why electrons don't emit energy continuously
- the appearance of emission spectra in which only discrete lines are observed.

Bohr's energy levels answer all three of these observations to some extent. Part of the conditions Bohr set for these energy levels is that the electron does not radiate energy while in these specific stable orbits. If the electrons don't continuously emit energy, the energy of the electron is constant, so the electron will not spiral into the nucleus.

The appearance of emission spectra was explained by electrons emitting the specific energy required to jump down (or transition) to a lower energy level. Since the allowable energy levels are set, only certain energies can be released, resulting in specific lines in the emission spectrum rather than a continuous spectrum. Emission spectra will be discussed further in Module 10.4.

HYDROGEN LINE SPECTRUM AND BOHR'S MODEL

Bohr's model was based on measurements of the hydrogen line spectrum. Based on these measurements Bohr realised the following:

- The **absorption spectrum** of hydrogen showed that the hydrogen atom was only capable of absorbing a small number of different frequencies and therefore energies of very specific values. That is, the absorbed energy was quantised.
- The emission spectrum of hydrogen showed that hydrogen atoms were also capable of emitting quanta of the exact energy value that they were able to absorb.
- If the frequency, and hence energy, of the incident light did not match a small number of values, the light would pass straight through the atom without any absorption occurring.
- Hydrogen atoms have an ionisation energy of 13.6 eV. Light of this energy or greater can remove an electron from a hydrogen atom, creating a positive ion.
- Photons of light with energies above the ionisation value for hydrogen are continuously absorbed.

Ionisation energy is the energy required to remove one electron from an atom of an element in the gas phase. It is measured in electron volts (eV).

Bohr labelled the possible electron orbits for the hydrogen atom with the energy level (n), and he was able to calculate the energy associated with each. Using these energy levels, he was able to theoretically predict the wavelengths of all the lines of the hydrogen emission spectrum using Planck's equation:

$$\Delta E = \frac{hc}{\lambda}$$

Figure 10.2.3 shows an energy level diagram for the hydrogen atom. These energies are expressed in terms of how much work needs to be done; how much energy needs to be added or absorbed—for the atom to be ionised (i.e. for the electron to be removed), which is shown as $n = \infty$. The point at which **ionisation** occurs is shown as $E = 0$, as the electron is no longer bound to the atom and so no longer has potential energy. For an electron in the ground state ($n = 1$) to escape the atom, 13.6 eV would be required.

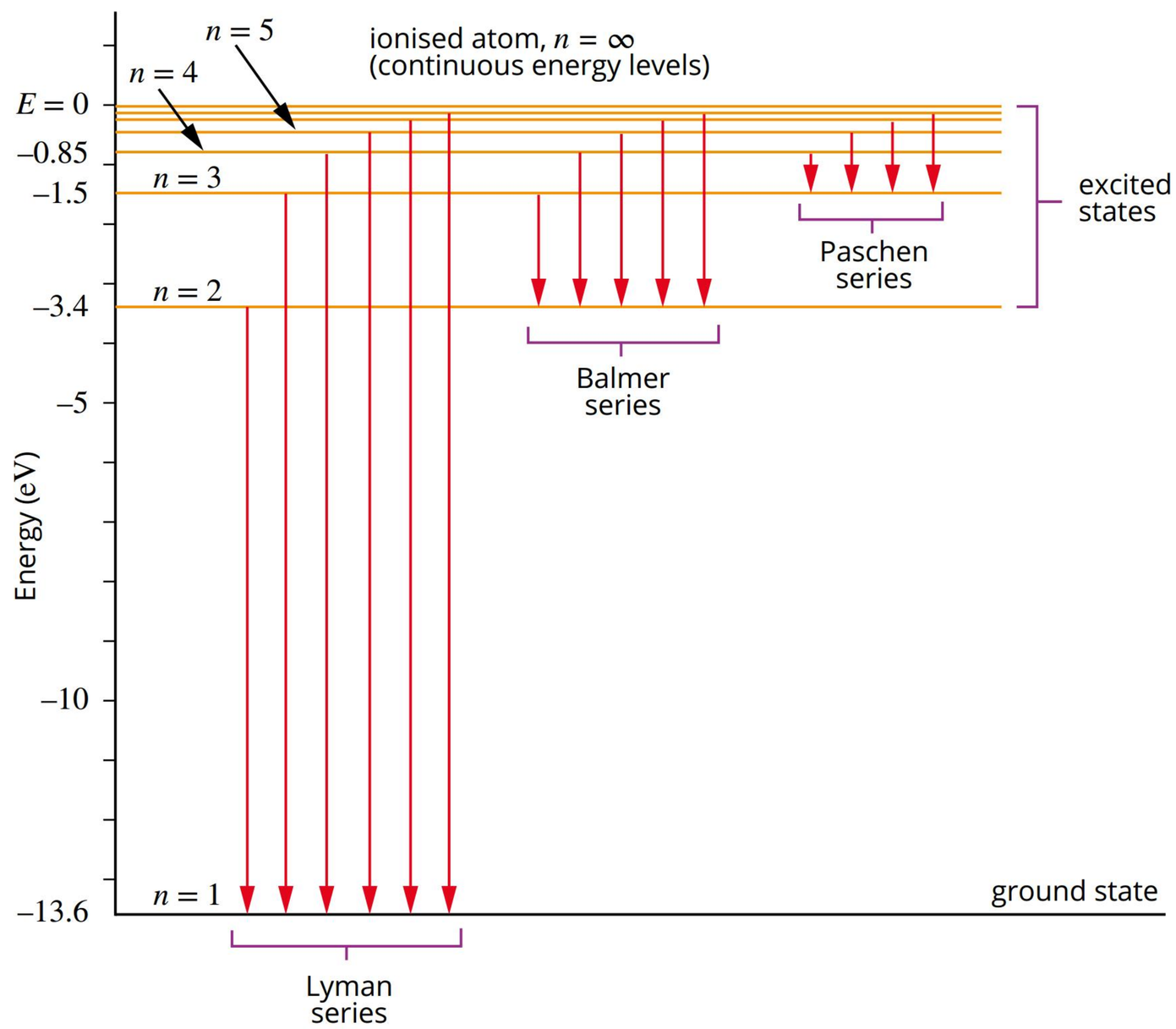


FIGURE 10.2.3 An energy level diagram for hydrogen shows the electron energy states. An electron in the ground state ($n = 1$) has an energy of (–)13.6 eV. For higher energy levels ($n > 1$), the energy levels can be seen to crowd together. Various names are given to electron transitions that finish at the same energy level but start at successively higher energy levels.

When a hydrogen atom gains energy, either by absorption, heating or from an electrical current, its electron moves from the ground level to one of the higher levels. This type of atom is described as 'excited'. Eventually, the electron will drop from the higher energy level to one of the lower levels and emit a photon with an energy equal to the difference in energy between the two levels.

You can see in Figure 10.2.3 that since a free electron (at $n = \infty$) must have zero potential energy, the energy levels within the atom are negative in value. To raise an electron from one energy level to another, the appropriate amount of energy must be delivered. As an electron falls, its energy value decreases. That is, it becomes a larger negative number.

Figure 10.2.3 also shows that the spectral lines of hydrogen can be explained in terms of electron transitions. The different series shown on the diagram (Lyman, Balmer, Paschen) represent the final level of specific transitions. The Balmer series, for example, shows transitions from various excited energy levels back to $n = 2$.

These transitions represent wavelengths of the visible lines of the hydrogen emission spectrum. This is covered in more detail in Module 10.4.

The energy of the photon emitted is the difference between the energy it starts with and the energy after the transition.

$$\Delta E = E_i - E_f$$

where

ΔE is the energy of the photon emitted

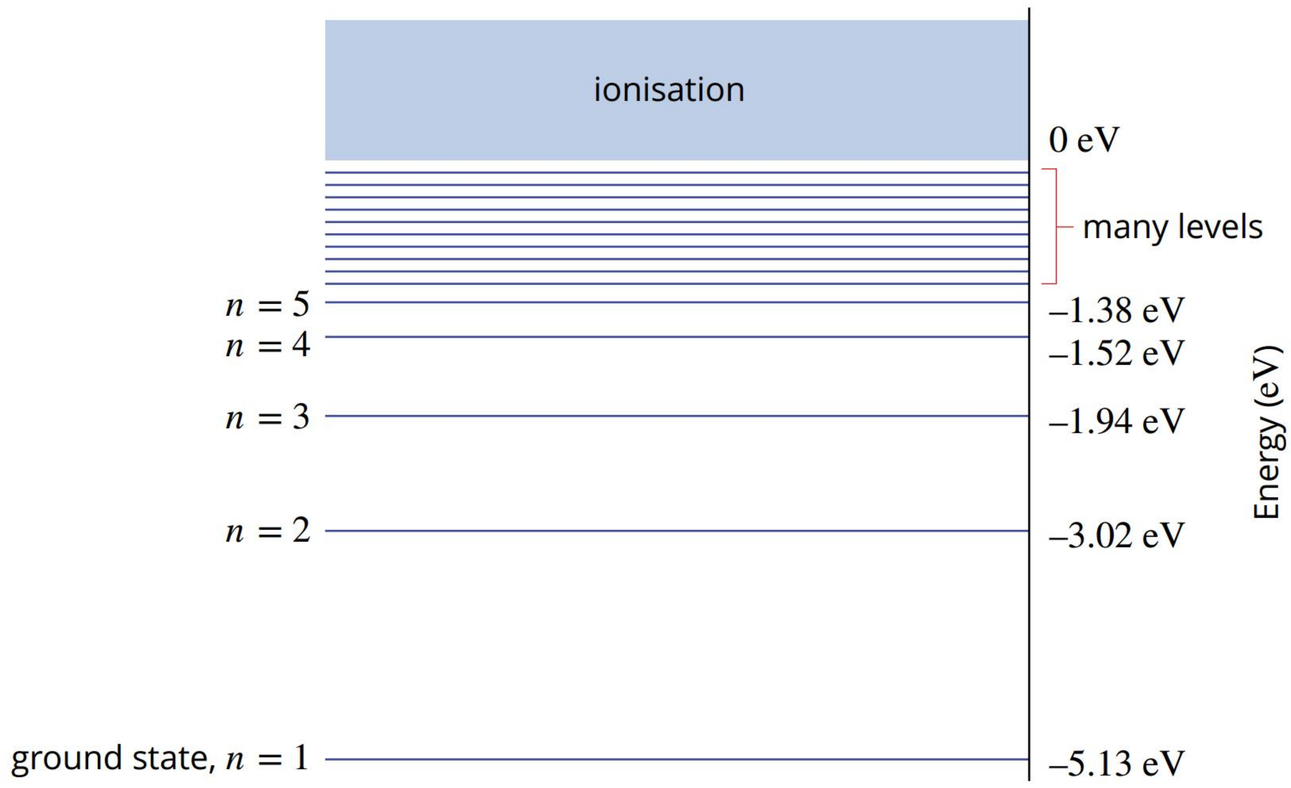
E_i is the energy of the initial energy level and

E_f is the energy of the final energy level.

Worked example 10.2.1

DETERMINING THE ENERGY EMITTED USING AN ENERGY LEVEL DIAGRAM

The energy levels for sodium gas are shown below. Calculate the energy and wavelength of the light that is produced in an emission spectra as an electron drops from the $n = 4$ to the $n = 2$ state.

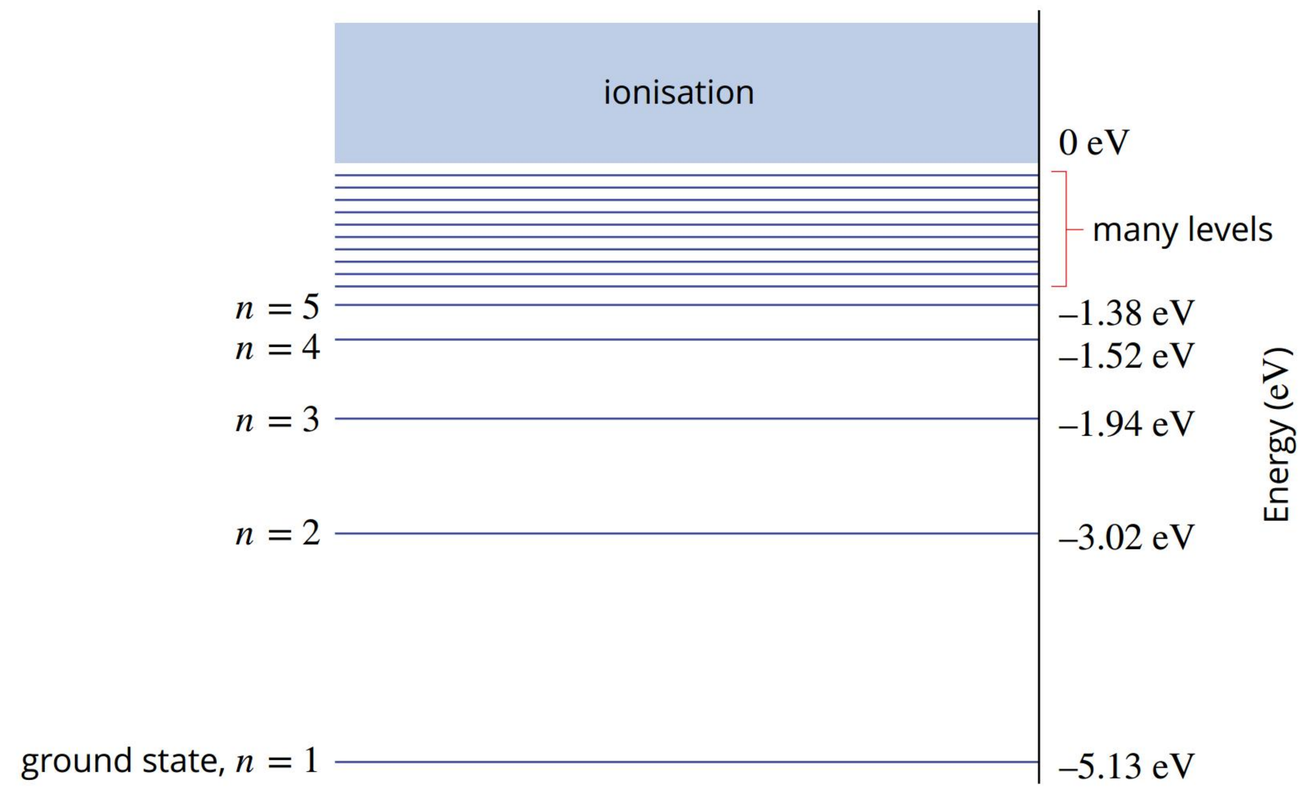


Thinking	Working
From the figure, find the energy (in eV) of each level involved.	$n_i = 4$, $E_i = -1.52\,\text{eV}$ $n_f = 2$, $E_f = -3.02\,\text{eV}$
Calculate the difference between these levels.	$\Delta E = E_i - E_f$ $= -1.52 - -3.02$ $= 1.50\,\text{eV}$
The energy difference between levels is equal to the energy of the photon emitted. Convert eV to J.	$1.50\text{ eV} = 1.50 \times (1.60 \times 10^{-19})$ $= 2.403 \times 10^{-19}\text{ J}$
Rearrange Planck's equation and calculate the wavelength.	$\Delta E = \frac{hc}{\lambda}$ $\lambda = \frac{hc}{\Delta E}$ $= \frac{(6.626 \times 10^{-34})(3 \times 10^{8})}{2.403 \times 10^{-19}}$ $= 8.27 \times 10^{-7}\text{ m}$

➤ Try yourself 10.2.1

DETERMINING THE ENERGY EMITTED USING AN ENERGY LEVEL DIAGRAM

The energy levels for sodium gas are shown below. Determine the energy and wavelength of the light that is produced as an electron drops from the $n = 4$ to the $n = 3$ state.



COMPARING RUTHERFORD'S AND BOHR'S MODELS

Bohr's model was based on Rutherford's model of the atom having a positively charged nucleus surrounded by electrons in constant motion. Bohr refined Rutherford's model by specifying that the electrons could only occupy specific orbitals at set distances from the nucleus, which was an application of the quantisation of energy that Planck proposed. A key difference between the two models is that, in Bohr's model, electron orbitals were stable, so electrons did not lose energy, unlike in Rutherford's model where the motion of electrons would cause the electrons to lose energy.

Notably though Bohr could not explain why the electrons should occupy these specific orbitals without losing energy or what physical significance these orbitals had. Bohr's model was also unable to explain the higher energy orbitals of multi-electron atoms, the continuous spectrum emitted by solids (Chapter 9) and could not predict all the complex features of hydrogen or multi-electron atom spectra.

Bohr's model of the hydrogen atom applied a quantum approach to the energy levels of atoms to explain a set of important, previously unexplained phenomena—the spectra of hydrogen. In principle, Bohr's work on the hydrogen atom could be extended to other atoms and, in 1914, the German scientists James Franck and Gustav Hertz demonstrated that mercury atoms contained energy levels similar to those of hydrogen atoms. To this extent, Bohr's model signified an important conceptual breakthrough.

10.2 Review

SUMMARY

- The Bohr model of the atom consists of a positive central nucleus with electrons in specific orbits around this nucleus.
- Niels Bohr suggested that electrons in atoms orbit the nucleus in specially defined energy levels, and no radiation is emitted or absorbed unless the electron can jump from its energy level to another.
- The energy emitted can be calculated using

$$\Delta E = E_i - E_f$$

- As electrons transition from a higher to a lower energy level, they emit a photon with energy equal to the difference in energy of the two energy levels.
- Energy levels are labelled $n = 1, 2, 3 \ldots$ where n is the energy level and $n = 1$ is the ground state and higher values of n are for excited states.

KEY QUESTIONS

Describe

1 Identify the force that keeps the electrons orbiting the positive nucleus in Bohr's model.

2 Describe the similarities between Rutherford's model and Bohr's model of the atom.

3 Are electrons able to exist between energy levels in Bohr's model of the atom?

4 What key evidence supports the idea of electrons occupying specific energy levels in the Bohr Model?

Apply

5 Photons of energy 0.42 eV are emitted by a particular atom as an electron returns from the excited state to the ground state. Determine the corresponding wavelength of these photons.

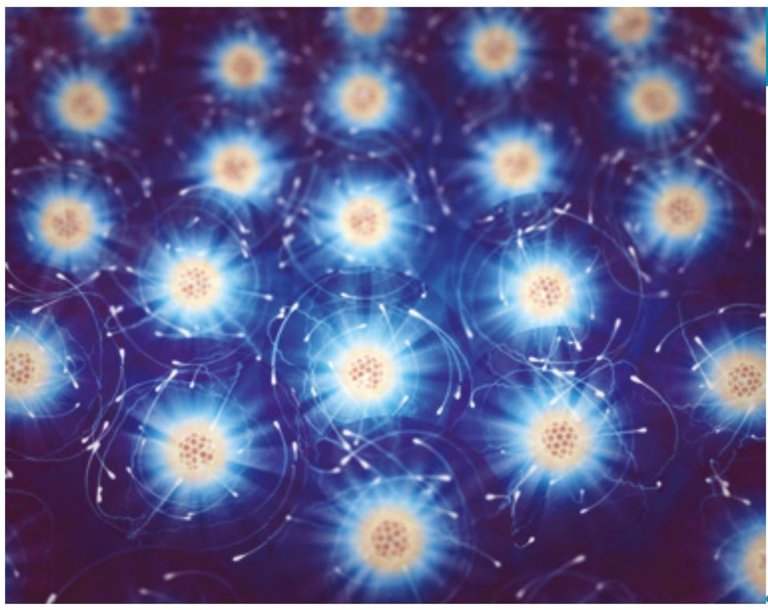
6 A hydrogen atom is in an excited state with the electron occupying the $n = 4$ energy state. What is the minimum energy required to ionise this atom? Refer to the hydrogen energy level diagram in Figure 10.2.3.

Analyse

7 The violet line of the hydrogen spectra is at 410 nm; calculate the energy (in J) of the photons corresponding to that wavelength.

8 An emission line of frequency 6.0×10^{14} Hz is observed when looking at the emission spectrum of a particular elemental gas. Calculate the energy, in joules, of photons corresponding to this frequency.

10.3 Wave–particle duality



BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- recall that photons exhibit the characteristics of both waves and particles
- describe the wave–particle duality of light by identifying evidence that supports the wave characteristics of light and evidence that supports the particle characteristics of light
- describe Planck's constant
- solve problems involving the energy, frequency, momentum and wavelength of a photon
- use the wavelength of electrons to calculate the radius of atomic orbitals.

In many ways, the wave and particle models for light seem fundamentally incompatible. Waves are continuous and are described in terms of wavelength and frequency. Particles are discrete and described by physical dimensions such as mass and radius.

To understand how these two sets of ideas can be used together, it is important to remember that scientists describe the universe using models. Models are analogies that are used to illustrate certain aspects of reality that might not be immediately apparent.

FIGURE 10.3.1 In the early 20th century, scientists worked closely together and built on each other's ideas. This photo shows attendees at the Fifth Solvay Conference on Protons and Electrons in Brussels in 1927. It was attended by great scientists, including Albert Einstein, Max Planck, Niels Bohr, Marie Curie, Paul Dirac, Erwin Schrödinger and Louis de Broglie. All these scientists contributed to the current knowledge of the universe, the atom and quantum mechanics.

UNDERSTANDING THE INTERSECTION OF THE WAVE AND PARTICLE MODELS

Through many experiments the model that sees light as both a wave and a particle has held firm. When light interacts with light, producing diffraction, interference and polarisation, light behaves as a wave. When light interacts with matter, as in the photoelectric effect and Compton scattering, light behaves as a particle.

Physicists have come to accept that light is not easily compared with any other classical entity. Light appears to be both a wave and a particle. This view of light is called **wave–particle duality**. Although this may seem somewhat paradoxical and counterintuitive, in the century since Einstein did his work establishing quantum theory, many experiments have supported this duality, and no scientist has come up with a better explanation.

The development of the quantum model of light was the work of many scientists at the time. Some of the greatest scientists of that time are shown in the historic photograph in Figure 10.3.1.

EVIDENCE FOR WAVE CHARACTERISTICS OF LIGHT

FIGURE 10.3.2 This is the diffraction pattern produced by white light passing through a diffraction grating. Diffraction allows waves to bend around an obstacle. When white light diffracts, longer wavelengths show more diffraction, producing a rainbow effect. The diffraction of light demonstrates its wave nature.

The key piece of evidence for the wave nature of light was provided well before quantum mechanics by the double-slit experiment (refer to Chapter 9), which demonstrated the interference of light. The main point to remember about the double-slit experiment is that when light is shone through two slits it produces a diffraction pattern (like a wave) rather than just two bright spots (like what would be expected from particles).

Interference isn't the only wave-like behaviour displayed by light. **Diffraction** is a property of waves and is the bending of a wave around the corners of an obstacle or aperture. It also accounts for how waves spread out as they travel. The bending is most pronounced when the obstacle is approximately the same size as the wavelength of the wave. The diffraction of light is readily observed in many situations, such as with diffraction gratings (Figure 10.3.2) and when light passes through a pinhole. Diffraction as light passes through the atmosphere produces the ring seen around bright objects. It also accounts for the fact that light can be seen from around a bend.

Another property of light that is evidence for its wave nature is polarisation. Recall that polarisation occurs when a transverse wave is only allowed to oscillate in one plane. One way light can be polarised is by passing it through a polarising filter (Figure 10.3.3), which blocks all other planes of oscillation of the electric field. Polarisation can only occur for transverse waves, so it is evidence for the wave nature of light.

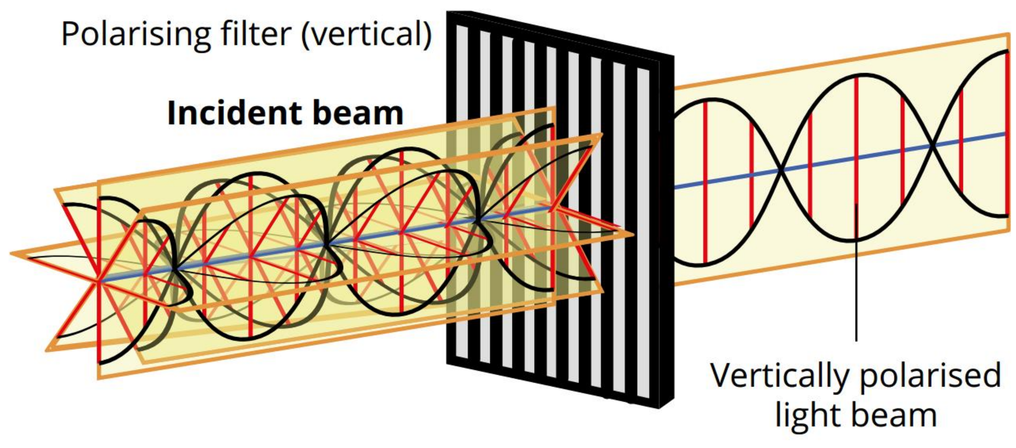


FIGURE 10.3.3 A diagram of the process of polarising light with only the electric field wave shown. For light that is polarised, the electric field wave oscillates in one plane only. Light must be a wave for this to occur.

EVIDENCE FOR PARTICLE CHARACTERISTICS OF LIGHT

Einstein was the key early proponent for the particle theory of light because this allowed for the explanation of the newly observed photoelectric effect (see Chapter 9). Recall that the photoelectric effect is the emission of electrons when light of sufficient frequency shines on a material. An incident photon transfers its energy to an electron, causing the electron to be ejected from the material (Figure 10.3.4). Wave theory predicted that as the intensity of light increased, the kinetic energy of the ejected photon would increase, and that if the light was very dim, there would be a time lag between the light and the subsequent ejection of a photon, as the energy built up. But this was not observed in experiments.

What was observed was that electrons were ejected only if the incident light was above a threshold frequency and that there was no time lag between photon absorption and electron emission. The kinetic energy of the electrons was also not dependent on intensity but rather the photon frequency. Einstein explained these results by proposing that light was a collection of discrete particles each with the energy hv (from Planck's work).

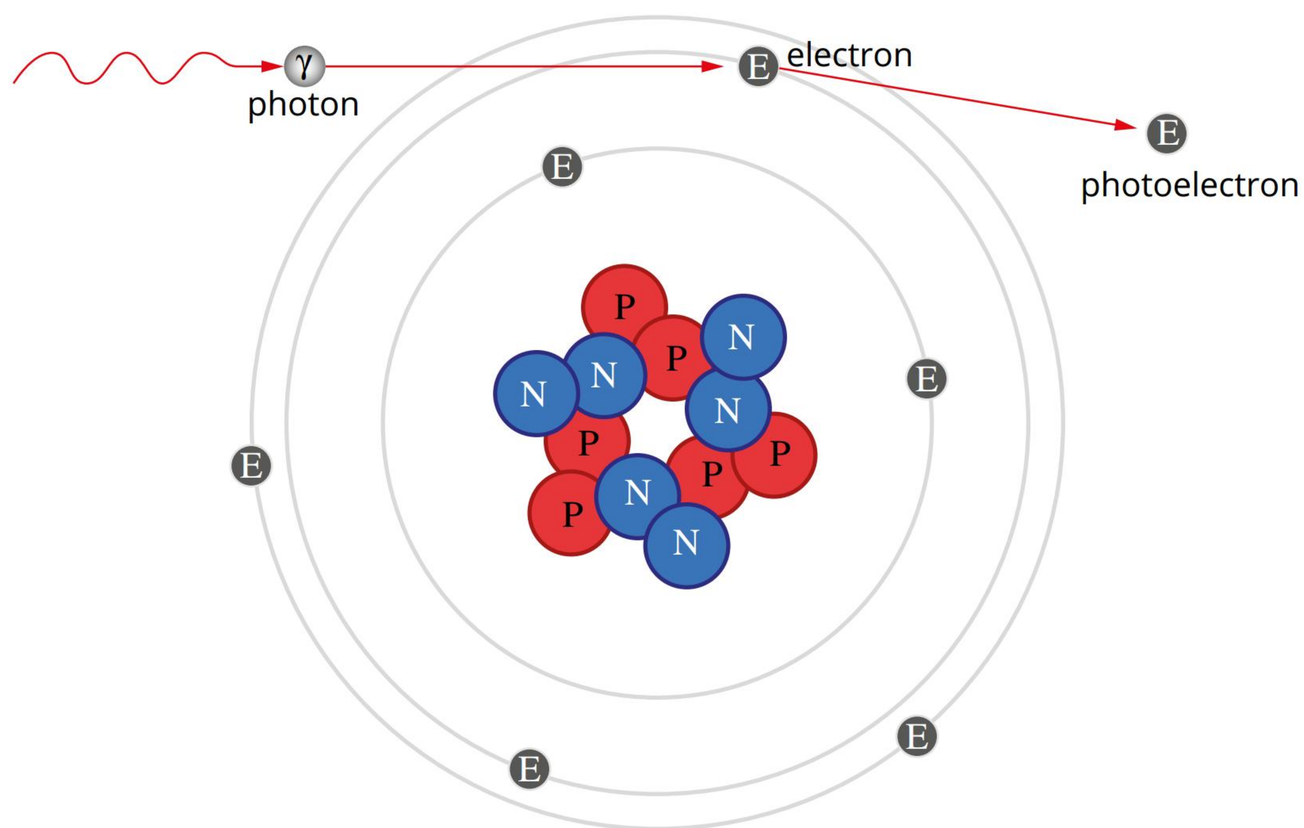


FIGURE 10.3.4 A diagram showing the process of the photoelectric effect. A photon transfers energy to the electron, providing enough energy for the electron to be ejected from the atom.

Photon momentum

A significant piece of evidence for the particle nature of light came from Arthur Compton's experiments. Compton's experiment demonstrated that light had momentum, which is a property of particles. Compton was looking for direct evidence of the particle nature of light and so studied collisions of photons with electrons. He fired X-rays at a graphite target that contained weakly bound electrons. In the collision, part of the energy of the photon is transferred to the electron, so it recoils and the photon is re-emitted in a different direction from the original so the overall momentum is conserved. The photons were emitted with a longer wavelength than the incident photons, indicating that the scattered photons had lost energy to the electron during the collision. This is known now as **Compton scattering**. The collision (Figure 10.3.5) is just as if tiny billiard balls are colliding. This can only be explained if the photon has momentum and is a particle.

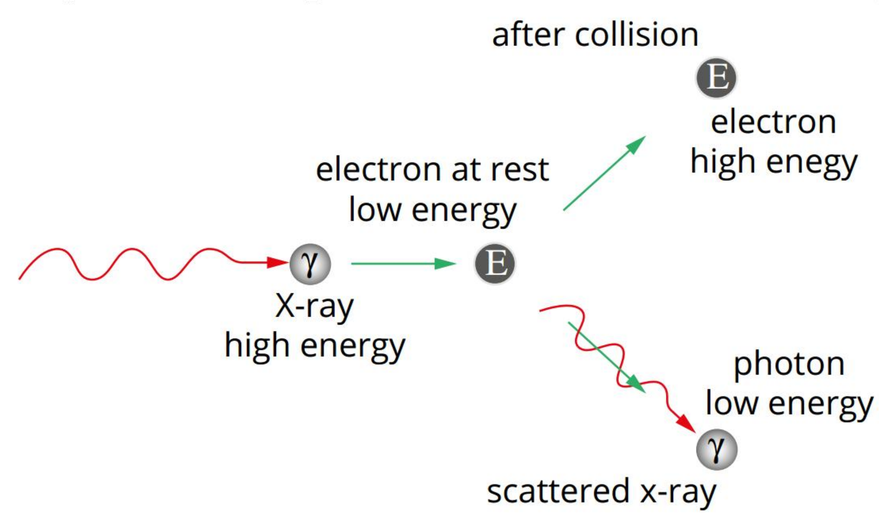


FIGURE 10.3.5 A diagram of Compton scattering showing photons were fired at electrons at rest. Part of the photon's energy is transferred to the electron and a photon with a longer wavelength, and thus less energy, is re-emitted in a new direction. This can only occur if photons have momentum.

In 1924, a French physicist named Louis de Broglie proposed a groundbreaking theory. He suggested that as light, which had long been considered to be a wave, sometimes demonstrated particle-like properties, then perhaps matter, which was considered to be made up of particles, might sometimes demonstrate wave-like properties.

He quantified this theory by equating Planck's equation (see Chapter 9), $\Delta E = \frac{hc}{\lambda}$, with Einstein's $\Delta E = \Delta mc^2$ (see Chapter 8):

$$\frac{hc}{\lambda} = mc^2$$

The wavelength (λ) of a photon is therefore given by:

$$\lambda = mc\frac{h}{p}$$

And the wavelength of a particle is given by:

$$\lambda = \frac{h}{mv}$$

Hence, the momentum of a photon can be found from:

$$\lambda = \frac{h}{p}$$

where:

λ is the wavelength of the particle (m)

h is Planck's constant

p is momentum of the particle (kg m s^{-1}).

An interesting consequence of de Broglie's hypothesis, $\lambda = \frac{h}{p}$, is that if a particle such as an electron has a wavelength λ, then a photon must have a momentum p. This is quite counterintuitive, since photons do not have any mass, and all photons travel at the speed of light, c in air or a vacuum. Nevertheless, de Broglie's equation allows the momentum of a photon to be calculated.

Worked example 10.3.1

CALCULATING PHOTON MOMENTUM

Calculate the momentum of a photon of red light with a wavelength of 650 nm.	
Thinking	**Working**
Convert 650 nm to m.	$650\,\text{nm} = 6.5 \times 10^{-7}\,\text{m}$
Transpose de Broglie's equation to make momentum, p, the subject.	$\lambda = \frac{h}{p}$ $p = \frac{h}{\lambda}$
Substitute in the appropriate values and solve for p.	$p = \frac{6.626 \times 10^{-34}}{6.5 \times 10^{-7}}$ $= 1.0 \times 10^{-27}\,\text{kg m s}^{-1}$

➤ Try yourself 10.3.1

CALCULATING PHOTON MOMENTUM

Calculate the momentum of a photon of blue light with a wavelength of 450 nm.

Clearly, the momentum of a single photon is tiny, which is why you will not feel any physical 'pressure' when light falls on you. However, it is possible to measure 'light pressure' using very sensitive equipment.

In interplanetary space, where other forces, such as friction, are negligible, light pressure can be used as a form of propulsion. Spacecraft such as the Mariner 10 and MESSENGER, which flew past Mercury and Venus, used deceleration caused by solar pressure to conserve fuel.

More recently, IKAROS is the first spacecraft to draw its primary propulsion from a solar sail. A traditional sail propels a ship using the change of momentum that occurs when air molecules bounce off it. Similarly, a solar sail gains propulsion from changes in photon momentum as light is reflected from it. The IKAROS spacecraft has a $196\,\text{m}^2$ reflective sail, which produces a thrust of 1.12 mN. An artist's impression of IKAROS is shown in Figure 10.3.6.

Light pressure is also very important when attempting to predict the paths of asteroids and considering potential impacts from Earth. The photon pressure from the Sun, over long periods of time, can change the orbit of asteroids.

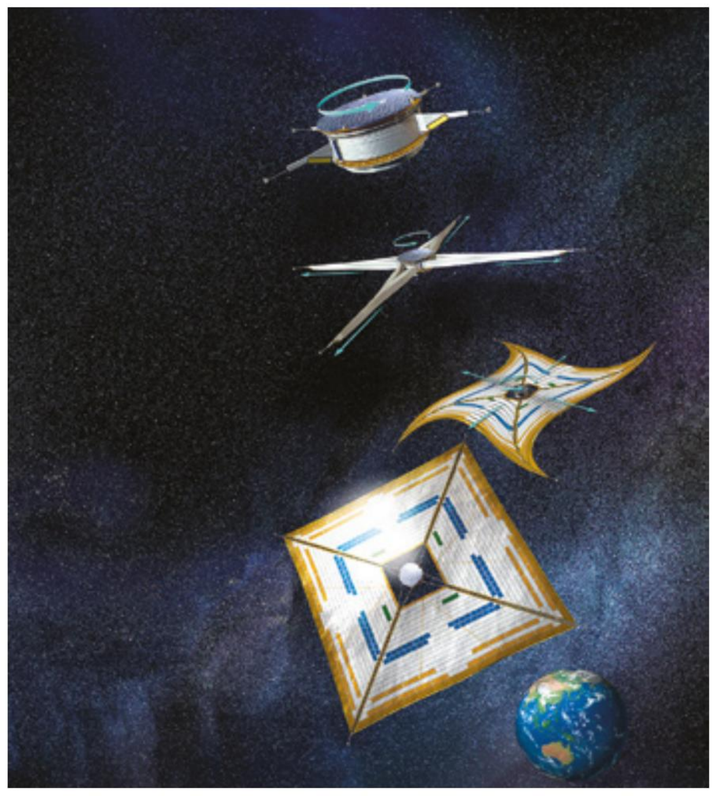


FIGURE 10.3.6 The IKAROS spacecraft is the first interplanetary spacecraft to use solar-sail technology.

Electron orbitals

Since de Broglie's hypothesis says that particles can demonstrate wavelike behaviour, electrons could now be described as matter waves and this suggested a new way to describe electron energy levels. If particles can be thought of as matter waves, then these matter waves must be able to maintain steady energy values if the particles are to be considered stable.

de Broglie applied his approach to the discussion of Bohr's model for the hydrogen atom. He viewed the electrons orbiting the hydrogen nucleus as matter waves. He suggested that the electron could only maintain a steady energy level if it established a **standing wave**. To fit a standing wave into a circular orbit, the orbit needs to be exactly equal to a whole number of wavelengths. This gives rise to only

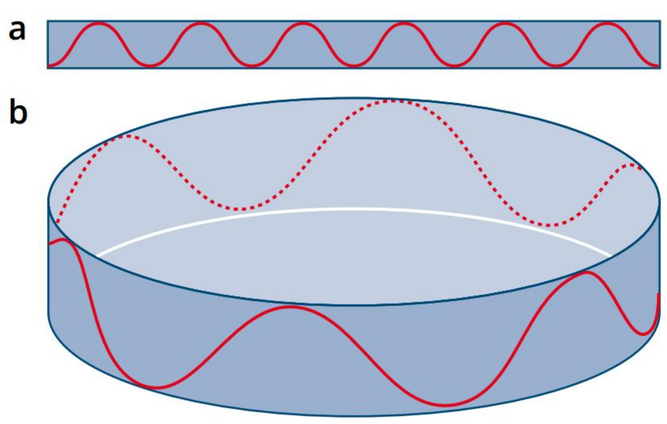


FIGURE 10.3.7 A standing wave pattern (a) can be looped around on itself to form a circle (b) where the circumference of the circle is equal to a whole number of wavelengths.

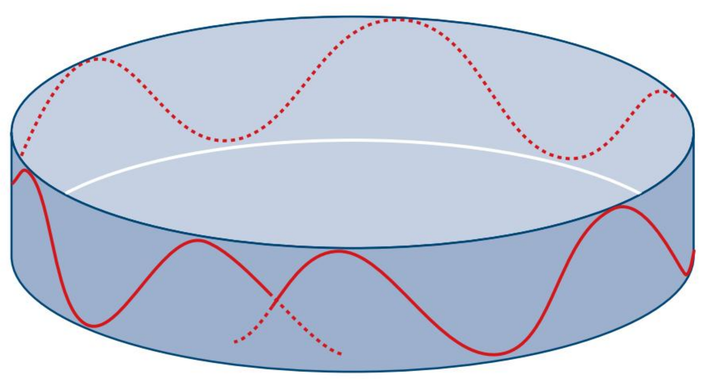


FIGURE 10.3.8 A circular standing wave pattern cannot be established if the circumference of the circle is not equal to a whole number of wavelengths.

certain orbits being possible—Bohr's quantised electron energy levels. As a standing wave, the electron doesn't radiate energy as it accelerates, so it can maintain its orbit and not spiral into the nucleus.

These standing waves can be visualised by imagining a conventional standing wave pattern, like that of a vibrating string, which was discussed in *Pearson Physics Queensland Units 1 & 2*, Chapters 9 and 10, being looped around in three dimensions with the ends touching (Figure 10.3.7).

If the circumference of the circle is not equal to a whole number of wavelengths, then destructive interference occurs, a standing wave pattern cannot be established and the orbit cannot represent an energy level (Figure 10.3.8).

The number of waves that fit around the orbit is n, the number of the energy level (Figure 10.3.9).

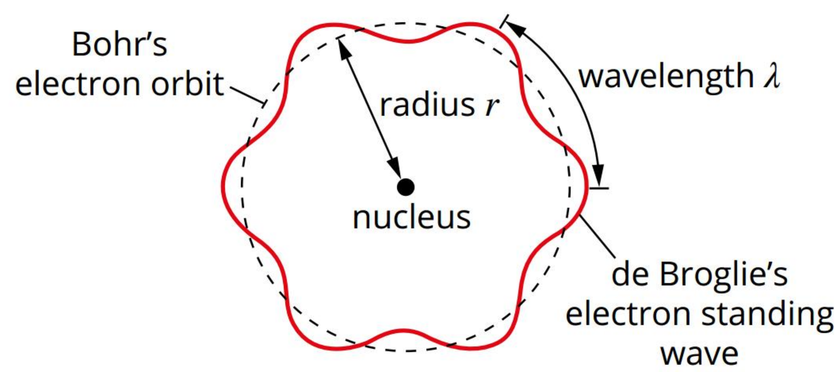


FIGURE 10.3.9 A representation of the standing wave electron orbitals proposed by de Broglie. Notice there are six wavelengths around this orbit so this is the energy level $n = 6$.

Consider the circumference of a circle:

$$C = 2\pi r$$

where

C is the circumference of the circle

r is the radius of the circle.

To be a standing wave, this circumference needs to be an integer number of wavelengths, so the condition becomes:

$$n\lambda = 2\pi r$$

where

λ is the wavelength of the electron in metres (m)

r is the radius of the circular orbit in metres (m)

n is an integer that is the energy level.

The stable orbits of the hydrogen atom are those for which the circumference is exactly equal to a whole number of electron wavelengths.

This equation can also be expressed in terms of the mass and velocity of the electron using $\lambda = \frac{h}{p}$:

$$\frac{nh}{p} = 2\pi r$$

Now replacing the momentum p with $p = mv$:

$$\frac{nh}{mv} = 2\pi r$$

Multiply both sides by mv:

$$nh = 2\pi mvr$$

Dividing both sides by 2π to get the equation into its standard form:

$$mvr = \frac{nh}{2\pi}$$

where

m is the mass of the electron (kg)

v is the velocity of the electron ($m\,s^{-1}$)

r is the radius of the circular orbit (m)

n is an integer that is the energy level

h is Planck's constant.

This specific form of this equation is known as Bohr's condition and the quantised energy levels of Bohr's model must satisfy this condition.

Worked example 10.3.2

CALCULATING THE RADIUS OF AN ENERGY LEVEL OF THE HYDROGEN ATOM

Calculate the radius of the $n = 1$ energy level of the hydrogen atom if the electron's kinetic energy is 2.176×10^{-18} J.

Thinking	Working
Rearrange the kinetic energy equation to make velocity the subject.	$E_k = \frac{1}{2}mv^2$ $v = \sqrt{\frac{2E_k}{m}}$
Use the kinetic energy provided and the rest mass of the electron to find the velocity of the electron. $m_e = 9.109 \times 10^{-31}$ kg	$v = \sqrt{\frac{2 \times (2.176 \times 10^{-18})}{9.109 \times 10^{-31}}}$ $= 2.1858 \times 10^6\,m\,s^{-1}$
Rearrange the equation $mvr = \frac{nh}{2\pi}$ to make r the subject of the equation.	$mvr = \frac{nh}{2\pi}$ $r = \frac{nh}{2\pi mv}$
Calculate the radius of the electron orbit for the ground state ($n = 1$).	$r = \frac{nh}{2\pi mv}$ $= \frac{1 \times (6.626 \times 10^{-34})}{2\pi(9.109 \times 10^{-31})(2.1858 \times 10^6)}$ $= 5.297 \times 10^{-11}$ m

➤ Try yourself 10.3.2

CALCULATING THE RADIUS OF AN ENERGY LEVEL OF THE HYDROGEN ATOM

Calculate the radius of the first excited state ($n = 2$) of the hydrogen atom if the electron's kinetic energy is 5.44×10^{-19} J.

This model of the atom is the basis for what physicists use today. The current model used by physicists has developed Bohr's model even further, using principles of quantum mechanics that are beyond the scope of this course. Rather than thinking about electrons following exact paths around the nucleus, they are better described by the *probability* of locating an electron in an electron cloud that has different shapes based on the waves that create it (Figure 10.3.10). How this is created is beyond the scope of this course, but you might have seen the results of this if you study chemistry and looked at the shapes of the *s*, *p*, *d* and *f* orbitals.

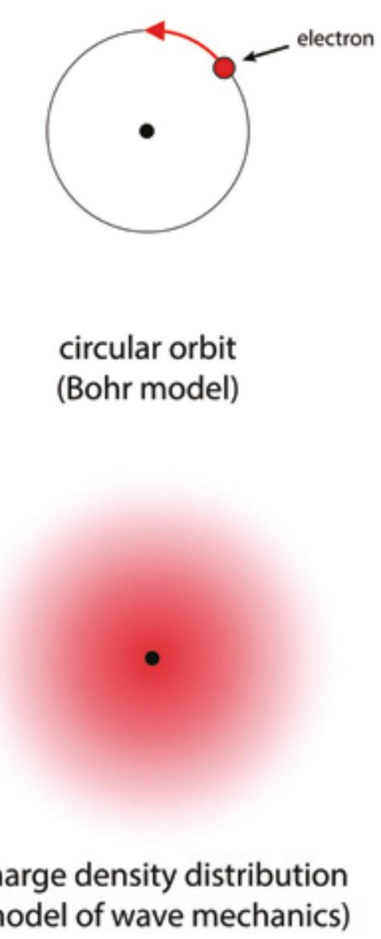


FIGURE 10.3.10 A comparison of the Bohr model and the current electron cloud model of the atom. The Bohr model predicts exact values of the location of the electron, while the wave mechanics model predicts a non-exact value of the electron's location.

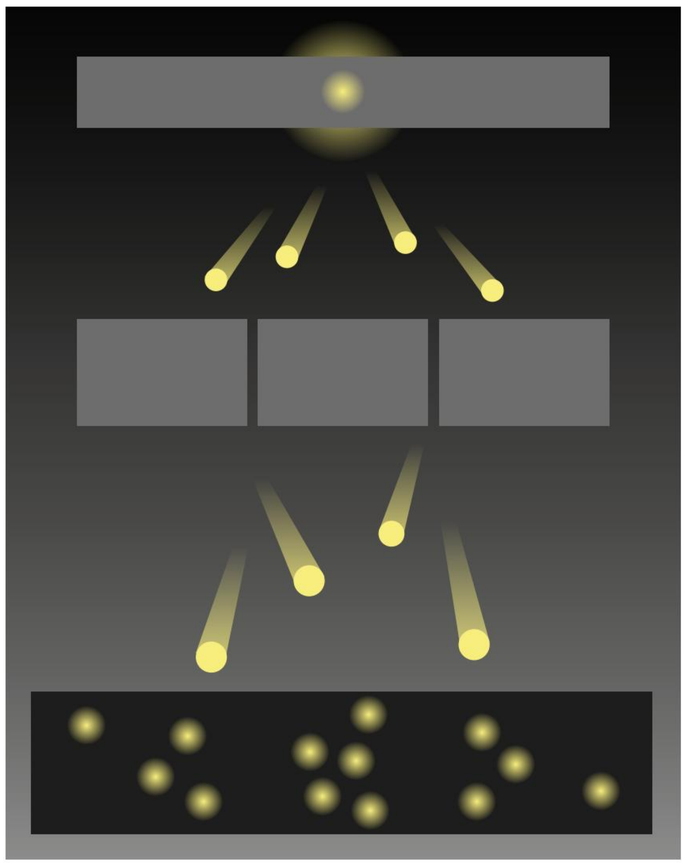


FIGURE 10.3.11 An interference pattern can be built up over time by the single-photon double-spit experiment, demonstrating the wave–particle duality of light.

Single photon double slit experiment

Over time, experiments provided evidence supporting both the wave and particle nature of light. In the **single-photon double-slit experiment,** extremely dim light sources were used, ensuring that only one photon passed through the apparatus at a time. Each single photon that passed through the apparatus made a single dot on the screen—but, over time, these experiments produced identical interference patterns to those done with bright sources (Figure 10.3.11). Each photon appeared to pass through both slits and produced interference with itself. The results of this experiment were consistent with wave behaviour by producing the interference pattern, even though single particles were passing through the slits, making single marks (particle nature), thus demonstrating the dual nature of light. It is important to understand that this is not the same experiment as the double slit experiment as it is performed with single photons and thus provides both wave and particle evidence.

10.3 Review

SUMMARY

- Evidence for wave characteristics of light includes:
  - diffraction
  - interference
  - polarisation.
- Evidence for particle characteristics of light includes:
  - photoelectric effect
  - Compton scattering, which showed light had momentum.
- When light interacts with light, generally it does so as a wave.
- When light interacts with matter, generally it behaves as a particle.
- At the atomic level, light and matter both exhibit wave-particle duality.
- The momentum of a photon (p) can be found using the de Broglie equation: $\lambda = \frac{h}{p}$.
- The wave nature of electrons explains the electron energy levels in Bohr's model of an atom, for which each energy level is a standing wave.
- The standing wave of the electron in Bohr's model of the atom needs to meet the following condition, known as Bohr's condition:

$$n\lambda = 2\pi r$$

This can also be written as $mvr = \frac{nh}{2\pi}$.

KEY QUESTIONS

Describe

1 List the evidence for considering light as a wave.

2 List the evidence for considering light to be a particle.

3 Identify whether the following scenarios are more easily explained by modelling light as a wave or as a particle.

a the 'rainbow effect' seen on the surface of a CD or DVD

b effect in a photovoltaic cell (solar cell)

c seeing the glow from a light on in a different room

Apply

4 When conducting a photoelectric effect experiment, Hollie and Adith correctly observe that the energy of emitted electrons depends only on the frequency of the incident light and is independent of the intensity.

a Explain how the particle model accounts for this observation.

b Explain why the wave model cannot account for this observation.

5 Sketch the de Broglie waves for the first three energy levels of an electron bound to the hydrogen nucleus.

6 Calculate the momentum of a photon with a wavelength of 410 nm.

7 The momentum of a photon is $6.28 \times 10^{-27}\,\text{kg m s}^{-1}$. Calculate the photon's wavelength.

Analyse

8 In the hydrogen atom, the ground state electron orbital has a radius of $r = 5.292 \times 10^{-11}$ m. Determine the wavelength of the electron in the ground state of the atom.

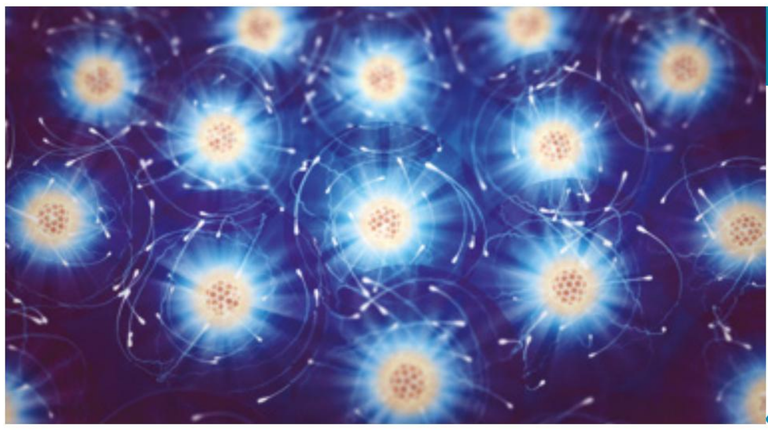
9 Calculate the kinetic energy of an electron in the $n = 4$ level of hydrogen if the radius of the orbit is 8.24×10^{-10} m.

10 Determine the radius of the $n = 3$ level of hydrogen, which has a kinetic energy of -1.5 eV, using $mvr = \frac{nh}{2\pi}$.

11 In the photoelectric effect, to just eject photoelectrons, sodium requires photons of a momentum of $1.47 \times 10^{-27}\,\text{kg m s}^{-1}$. Determine the work function for sodium.

12 What is the speed of the electron in the ground state of hydrogen if the radius of the electron orbital in the ground state is $r = 5.292 \times 10^{-11}$ m.

10.4 Atomic spectra



BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- explain how the Bohr model of the hydrogen atom integrates light quanta and atomic energy states to explain the specific wavelengths in the hydrogen line spectrum
- solve problems involving the line spectra of simple atoms using atomic energy states or atomic energy level diagrams.

The analysis of atomic and molecular spectra is important in physics, chemistry and astronomy. It is used to study the structure of different atoms and molecules, and to determine constituent components of complicated substances.

Isaac Newton was the first to describe the rainbow of colours that form white light as a spectrum. In the 1800s as the available optics improved, physicists such as William Wollaston and Joseph von Fraunhofer noticed that the Sun's spectrum was not the continuous spectrum expected, but rather there were missing lines of colour. Scientists were also looking at the spectra of terrestrial-based light sources such as flames and examining the spectra of different substances. With improvements in technology, such as diffraction gratings and the Bunsen burner, there were developments in the field of analytical spectroscopy.

HYDROGEN LINE SPECTRA

Hydrogen is the simplest atom, as it consists of just one electron and one proton. The lack of extra particles minimises interactions within the atom, making the hydrogen spectrum easier to model. Hydrogen is also predominant in stars for which some of the earliest spectra have been observed, so it was the first atomic spectrum examined in detail. The visible emission spectra of hydrogen and helium can be seen in Figure 10.4.1.

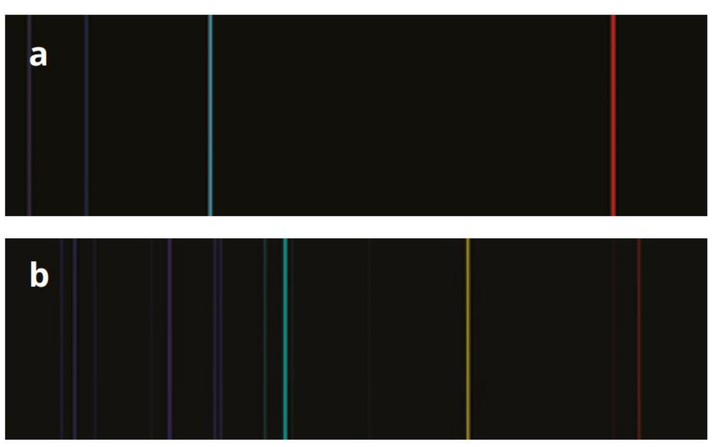


FIGURE 10.4.1 The visible spectral lines for hydrogen (a) and helium (b). The spectral lines of an element are unique to that element and are produced as electrons transition between different energy levels within the atom.

In Module 10.2, Bohr's model of the atom, including quantised energy levels for the electrons, was used to explain the hydrogen atom and the observed spectral lines. Recall that the spectral lines are produced by electron transitions between the quantised energy levels. The variable n represented quantised energy levels and is used to describe the transitions. The wavelength of each spectral line is determined by its energy. The spectral lines are the same wavelength in both emission and absorption spectra.

Emission spectra

When elements are heated to high temperatures or have an electrical current passed through them, they produce light. You will recall from Module 10.2 that when atoms absorb energy they become 'excited' and eventually the atom will return to the 'unexcited', or ground, state. When this happens, the energy that had been absorbed is released as a single photon. The colour of this photon will depend on the amount of energy it has.

FIGURE 10.4.2 The different metals used in fireworks are responsible for the colours in this display. For example, strontium gives red, sodium gives yellow and copper gives green.

Since atoms can usually have several different excited states, they can produce a number of different colours. The combination of colours produced by a particular element is distinctive for that element (Figure 10.4.2) and is known as its emission spectrum.

Absorption spectra

In 1814, the German physicist Joseph von Fraunhofer reported several dark lines appearing in the spectrum of sunlight (Figure 10.4.3).

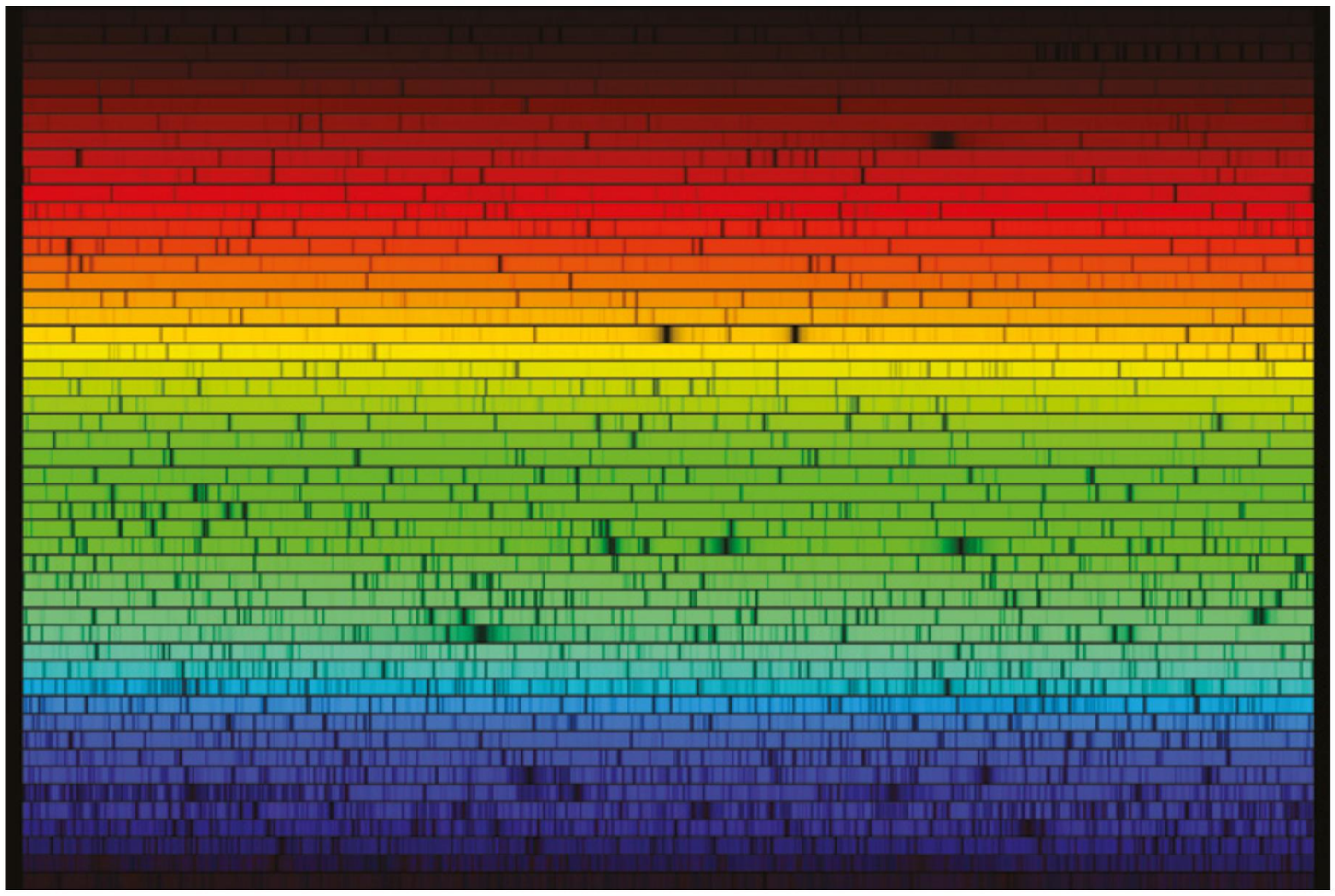


FIGURE 10.4.3 The spectrum of sunlight contains some missing colours known as Fraunhofer lines.

When Fraunhofer passed sunlight through a prism, he observed the spectrum (as expected) but he also noticed that there were some colours 'missing' from the spectrum. The missing colours appeared as black lines at various points along the spectrum. These apparently missing colours came to be known as Fraunhofer lines. It was later recognised that these lines corresponded to the colours emitted when certain gases are heated. It was deduced that the dark lines were due to these colours (wavelengths) being absorbed by gases as light made its way through the outer atmosphere of the Sun. This absorption spectrum allowed astronomers to determine that the Sun is largely composed of hydrogen with small quantities of helium and some other heavier elements.

Absorption spectra are a valuable tool for scientists who wish to know what elements are present in a sample of gas or in a solution, so their use is not limited to analysing stars. Light is directed through a cool sample of a gas or through a solution containing a particular element or compound. Particular frequencies of light will be absorbed by the elements present in the sample, so that on viewing the spectrum, this particular frequency will be 'missing'. The particular frequencies that are absorbed are unique to each type of atom. For this reason, by analysing which frequencies are missing, scientists can determine exactly what elements and molecules are present in the sample.

The lines in the absorption spectrum of an element have the same wavelengths, and thus energies, as the lines in the emission spectrum of that element.

Interpreting atomic spectra

In an emission spectrum, the electrons emit energy as they transition back to a lower energy level. On an energy level diagram, this is depicted with an arrow going downwards from a higher to a lower energy level, as in the hydrogen emission spectrum in Figure 10.4.4a. In an absorption spectrum, the electron is gaining energy (from the light) so it is transitioning from a lower to a higher energy level. Absorption is shown by an arrow going upwards from a lower to a higher energy level, as seen in the absorption spectrum for a singularly ionised helium ion in Figure 10.4.4b. Singularly ionised helium is a hydrogen-like ion, because it has one electron and its energy levels can be calculated using an extended version of the Rydberg formula, discussed on page 277. Energy level diagrams can be used to analyse atoms other than hydrogen if the energies are provided, although calculating these energy levels is much more complicated. Remember that the absorption transition and the emission transmission for the same energy levels will have the same energy.

On an energy level diagram, absorption transitions are shown with an arrow upwards and emission is shown with an arrow downwards.

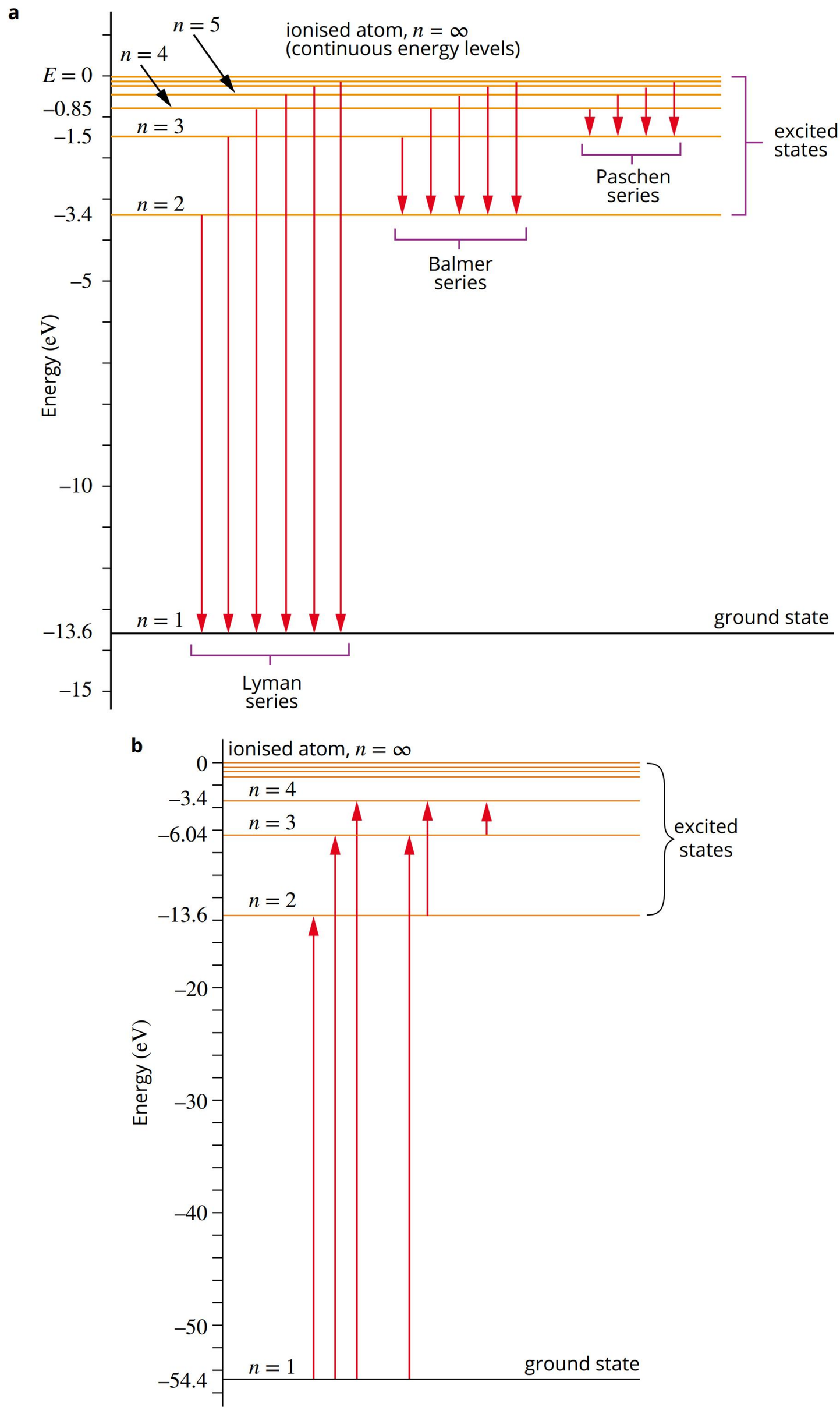


FIGURE 10.4.4 (a) An energy level diagram for hydrogen. Notice the arrows pointing downwards. This indicates an emission spectrum. (b) An energy level diagram for the singularly ionised helium ion. Notice the arrows pointing upwards. This indicates an absorption spectrum.

Worked example 10.4.1

DISTINGUISHING BETWEEN ABSORPTION AND EMISSION TRANSITIONS

An electron transitions from the $n = 3$ energy level to the $n = 2$ energy level. Identify whether this is an emission or absorption transition and describe the way this would be shown on an energy level diagram.	
Thinking	**Working**
Identify n_i and n_f.	$n_i = 3$ $n_f = 2$
The energy level has decreased, so this is emission.	The transition from the $n = 3$ energy level to the $n = 2$ energy level is an emission transition. Emissions are shown with a downwards arrow on an energy level diagram.

➤ Try yourself 10.4.1

DISTINGUISHING BETWEEN ABSORPTION AND EMISSION TRANSITIONS

An electron transitions from the $n = 3$ to the $n = 5$ energy level. Identify whether this is an emission or absorption transition and describe the way this would be shown on an energy level diagram.

Sketch in your notebook the hydrogen energy level diagram shown in Figure 10.4.4b. On this diagram draw an arrow to show the transition between the $n = 3$ and $n = 5$ energy levels.

In Module 10.2 the most common convention of labelling atomic energy levels was described. By this convention, the energy given is the amount of energy required to remove an electron from an atom. This convention gives all the energy values as negative and the ionisation energy level ($n = \infty$) has a value of 0 eV. An alternative convention is one in which the ground state ($n = 1$) is allocated 0 eV and higher levels have positive values. It is important to be able to interpret both conventions. The two conventions can be seen by comparing the energy level diagrams in Figure 10.4.4 and the energy level diagram for doubly ionised lithium in Figure 10.4.5. Doubly ionised lithium is of interest as it is a hydrogen-like ion in that is has only one electron.

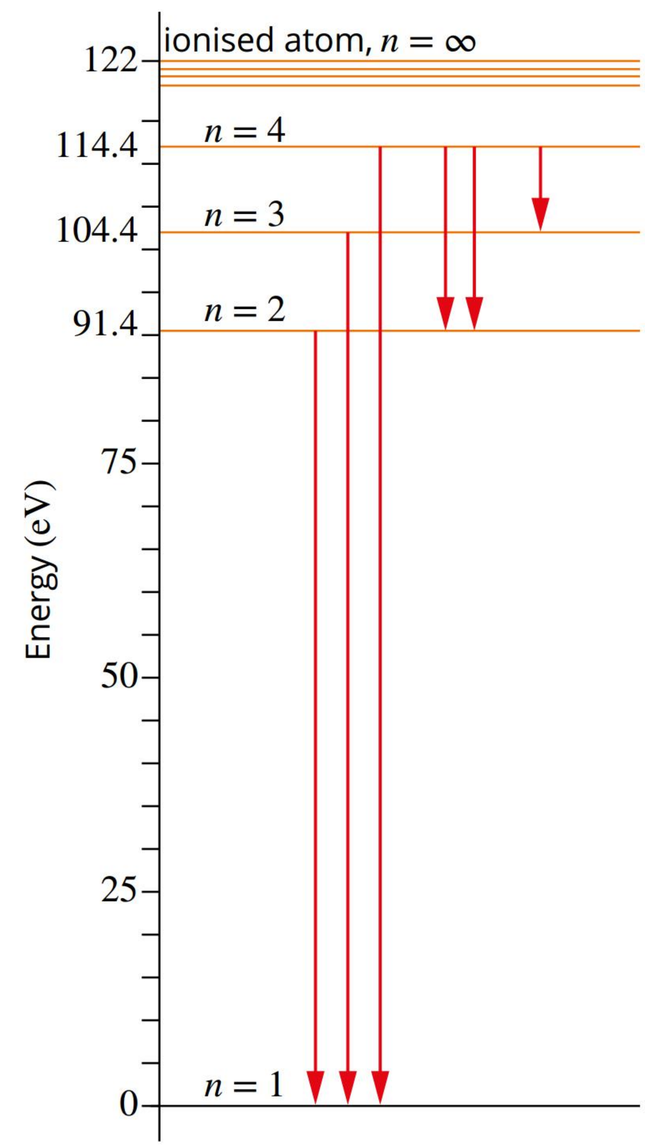


FIGURE 10.4.5 An energy level diagram for the doubly ionised lithium ion (Li^{2+}) showing the alternative labelling convention for energy levels.

Using energy level diagrams to determine transitions

Recall that in Module 10.2 the energy difference of a transition was defined as the difference in energy between the initial and final states, and was calculated using energy level diagrams. This gives the energy of an absorbed or emitted photon, and combined with the use of Planck's equation, the wavelength of that photon can be determined. This is one method to calculate the hydrogen spectral lines.

Each possible electron transition produces light of a different energy. The energy corresponds to a different coloured line in the emission or absorption spectrum for that atom. The greater the energy emitted, the higher the frequency and the shorter the wavelength of the light.

RYDBERG FORMULA

Before Bohr's model explained the hydrogen emission spectra, scientists were hunting for a mathematical relationship between the lines that would also allow for the prediction of further lines. In 1885, Joseph Balmer found a relationship that described the visible lines of the hydrogen spectra as well as predicting a line in the ultraviolet region that hadn't yet been observed. This turned out to be a special case of a more general formula discovered by Johannes Rydberg in 1888.

The Rydberg formula for hydrogen

$$\frac{1}{\lambda} = R\left(\frac{1}{n_f^2} - \frac{1}{n_i^2}\right)$$

where

λ is the wavelength of the radiation emitted

R is the Rydberg constant ($1.097 \times 10^7\ \text{m}^{-1}$)

n_i is the number of the initial energy level of the transition

n_f is the number of the final energy level of the transition.

The Rydberg formula (or equation) was originally used to predict spectral lines that hadn't yet been observed. Rydberg's formula predicted that there should be spectral lines in other parts of the electromagnetic spectrum. The ultraviolet series was later observed by Theodore Lyman, and two different infrared series were observed by Friedrich Paschen and Frederick Brackett. This formula only applies for hydrogen but can be extended for other hydrogen-like elements such as He^+ and Li^{2+}.

Rydberg arrived at his formula by empirical methods, but it can be derived using Bohr's condition and by looking at the energy of the electron.

Worked example 10.4.2

USING THE RYDBERG EQUATION TO CALCULATE HYDROGEN ENERGY LEVELS

Calculate the wavelength (in nm) of the transition from $n = 5$ energy level to the $n = 2$ energy level in hydrogen using the Rydberg equation.	
Thinking	**Working**
Identify n_i and n_f.	$n_i = 5$ $n_f = 2$
State the Rydberg equation.	$\frac{1}{\lambda} = R\left(\frac{1}{n_f^2} - \frac{1}{n_i^2}\right)$
Substitute the values for n_i, n_f and the Rydberg constant into the Rydberg equation.	$\frac{1}{\lambda} = (1.097 \times 10^7) \times \left(\frac{1}{2^2} - \frac{1}{5^2}\right)$
Solve the right-hand side of the equation.	$\frac{1}{\lambda} = (1.097 \times 10^7) \times \left(\frac{1}{4} - \frac{1}{25}\right)$ $= (1.097 \times 10^7) \times 0.210$ $= 2.304 \times 10^6\ \text{m}^{-1}$
Find the inverse of both sides to solve for the wavelength.	$\lambda = \frac{1}{2.304 \times 10^6}$ $= 434.0\,\text{nm}$

➤ Try yourself 10.4.2

USING THE RYDBERG EQUATION TO CALCULATE HYDROGEN ENERGY LEVELS

Calculate the wavelength absorbed by a hydrogen atom when its electron goes from the $n = 1$ energy state to the $n = 6$ energy state. Use the Rydberg equation.

Worked example 10.4.3

USING THE RYDBERG EQUATION TO DETERMINE ENERGY LEVELS

Visible light of 656 nm was emitted from a hot sample of hydrogen gas. Determine the energy levels involved in this transition. For hydrogen, visible light is emitted by the transitions indicated by the Balmer series in hydrogen emission spectrum diagram (in Figure 10.4.4a) where the final energy level is $n = 2$.

Thinking	Working
Rearrange the Rydberg equation to move n_i to the left-hand side of the equation.	$\frac{1}{\lambda} = R\left(\frac{1}{n_f^2} - \frac{1}{n_i^2}\right)$ $\frac{1}{R\lambda} = \frac{1}{n_f^2} - \frac{1}{n_i^2}$ $\frac{1}{n_i^2} = \frac{1}{n_f^2} - \frac{1}{R\lambda}$
Substitute the values for λ, n_f and the Rydberg constant into the equation.	$\frac{1}{n_i^2} = \frac{1}{2^2} - \frac{1}{(1.097\times10^7)(656\times10^{-9})}$ $= 0.111$
Solve for n_i.	$n_i^2 = \frac{1}{0.111}$ $n_i = \sqrt{\frac{1}{0.111}}$ $= 3$
State the energy levels involved in this transition.	The emission is from the $n = 3$ energy level to the $n = 2$ energy level of hydrogen.

➤ Try yourself 10.4.3

USING THE RYDBERG EQUATION TO DETERMINE ENERGY LEVELS

Light with wavelength of 1875 nm was produced from a hydrogen gas discharge tube. The final energy level for this transition was $n = 3$. Determine the initial energy level.

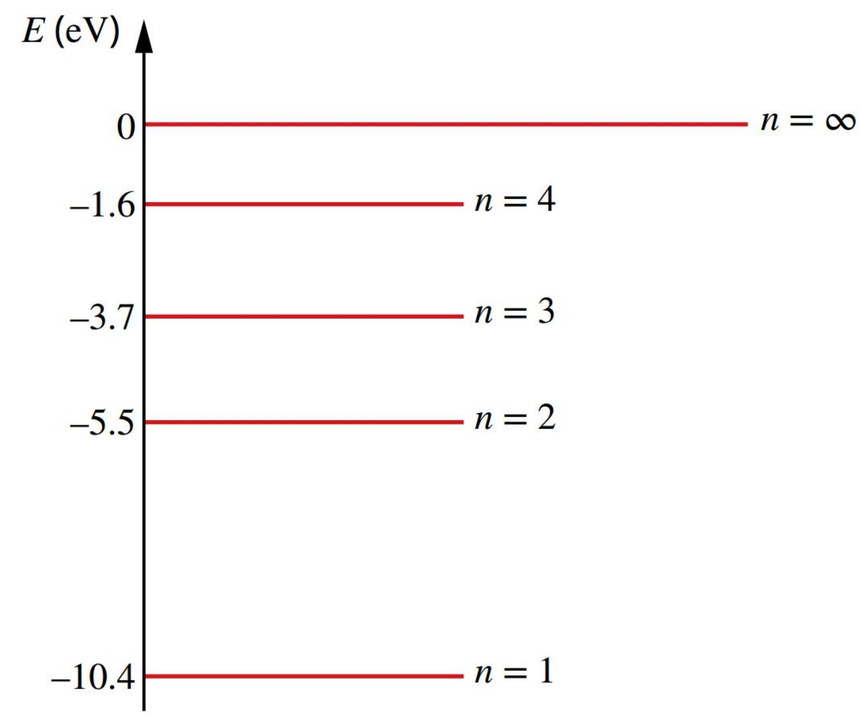
ABSORPTION SPECTRA AND BOHR MODEL

An electron ordinarily occupies the lowest energy orbit. Incident light carrying insufficient energy to raise an electron from this lowest energy level to the next level will be unable to be absorbed by the atom. It would simply pass straight through. If light, with greater energy than the ionisation energy of an atom, is incident, then any light energy will be absorbed. In this case, the excess photon energy will simply translate to extra kinetic energy for the released electron. If light of an energy equal to a difference in energy levels is incident, then the electron at that level will absorb all the photon's energy and move up to the corresponding level.

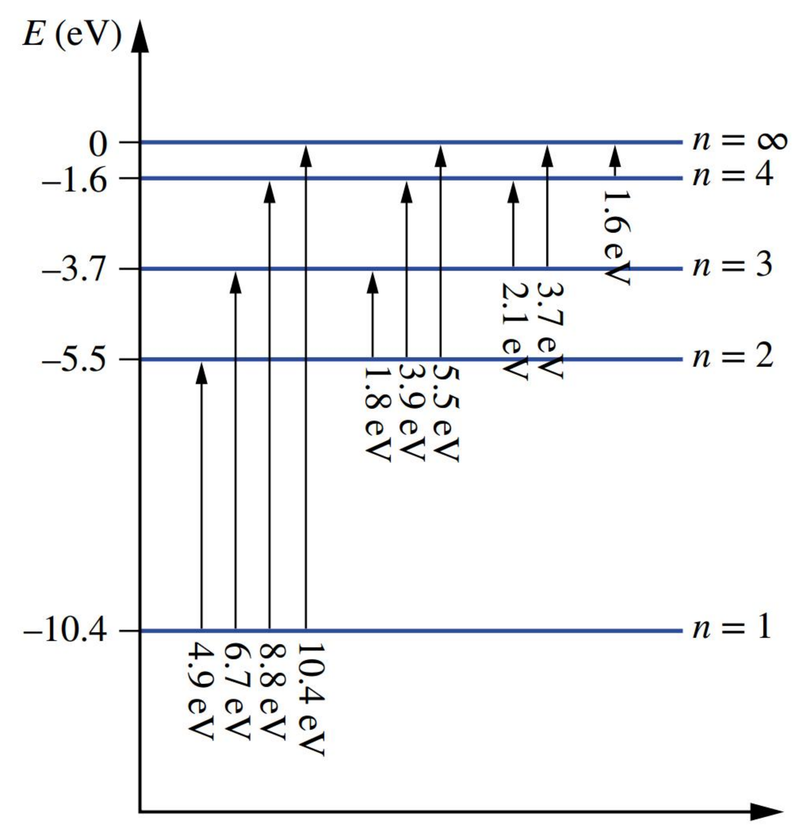
Worked example 10.4.4

ABSORPTION OF PHOTONS

Some of the electron energy levels for atomic mercury are shown in the diagram below.



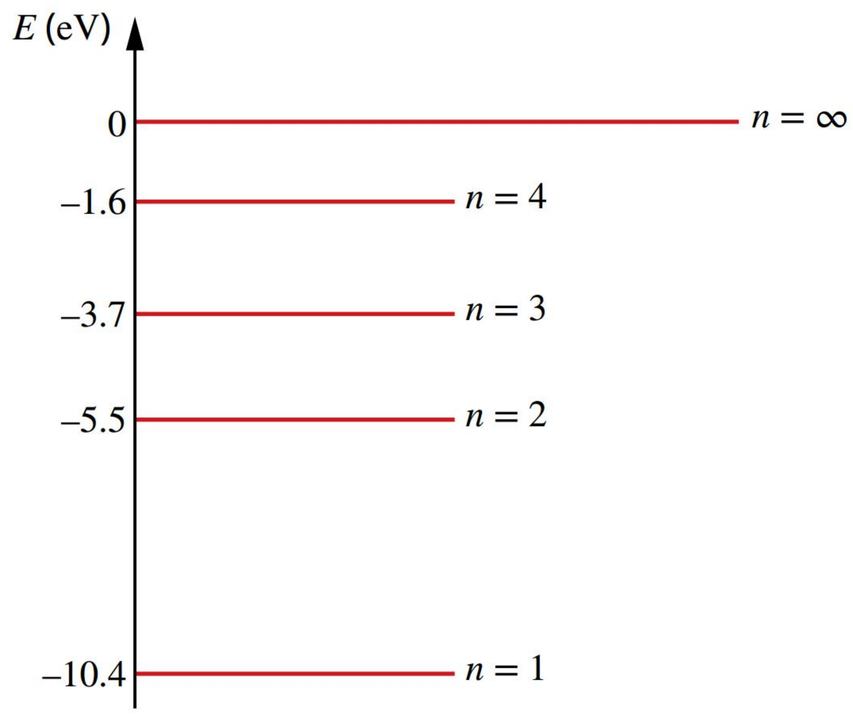
Ultraviolet light with photon energies 4.9 eV, 5.0 eV and 10.50 eV is incident on some mercury gas. Determine what could happen as a result of the incident light, assuming all electrons are in the ground state of the atom.

Thinking	Working
Check whether the energy of each photon corresponds to a difference between energy levels by determining the difference in energy between each level.	
Compare the energy of each photon with the energies determined in the previous step. Comment on the possible outcomes.	A photon of 4.9 eV corresponds to the energy required to promote an electron from the ground state to the first excited state (n = 1 to n = 2). The photon will be absorbed. A photon of 5.0 eV cannot be absorbed as there is no energy level above the ground state that corresponds exactly to 5.0 eV. A photon of 10.5 eV will ionise the mercury atom. The ejected electron will leave the atom with 0.1 eV of kinetic energy.

➤ Try yourself 10.4.4

ABSORPTION OF PHOTONS

Some of the energy levels for atomic mercury are shown in the diagram below.



Light with photon energies 6.7 eV, 9.0 eV and 11.0 eV is incident on some mercury gas. Determine what could happen as a result of the incident light, assuming all electrons are in the ground state.

10.4 Review

SUMMARY

- An emission spectrum is produced by energised atoms as electrons emit energy as they transition back to a lower energy level. The spectrum for each element is unique.
- An absorption spectrum is produced by atoms absorbing specific wavelengths from radiant light. This yields the full spectrum with those specific wavelengths missing. The wavelengths absorbed by an atom are the same as the wavelengths that are emitted when the atom is in an excited state.
- An electron in an atom which drops between energy levels emits a photon of energy equal to the difference between the energy levels. The energy of the photon determines the wavelength of the photon.
- The energy of a transition can be determined using the difference in energy between the two energy levels. These energies can be found on the energy level diagram for that species.
- The wavelength of the radiation emitted for hydrogen can be calculated using the Rydberg equation:

$$\frac{1}{\lambda} = R\left(\frac{1}{n_f^2} - \frac{1}{n_i^2}\right)$$

10.4 Review *continued*

KEY QUESTIONS

Describe

1 Identify the link between an atom's emission spectrum and its structure.

2 Describe how the energy levels (not the transitions) within an atom are commonly represented on a graph.

3 If the initial energy level is $n = 1$, determine whether an absorption or emission process is occurring.

Apply

4 James is arguing that when an electron falls from a higher energy level to a lower energy level, the atom emits a random amount of energy (as a photon). Explain what is incorrect with that statement.

5 Explain how an absorption spectrum is produced and describe what it looks like.

6 A transition occurs from the $n = 5$ energy level to the $n = 7$ energy level of an atom. Determine if this is an absorption or emission transition and explain how to determine this.

Analyse

Use the hydrogen energy level diagram in Figure 10.4.4a on page 274 to answer Questions **7–10.**

7 Determine the energy level, or levels, of the electron in the hydrogen atom that is the:

- **a** ground state
- **b** ionisation level
- **c** excited states.

8 Calculate the energy of the photon that is released as an electron in the $n = 2$ excited state of a hydrogen atom drops back to the ground state. Calculate the wavelength of the photon.

9 Light with the following energies is shone on a sample of hydrogen gas. Determine what could happen to the hydrogen's electron for each of these energies:

- **a** 10.2 eV
- **b** 5 eV
- **c** 14.2 eV.

10 Calculate the wavelength of the photons absorbed in the transition from ground state to the $n = 4$ excited state in hydrogen.

11 Using the double ionised lithium energy level diagram in Figure 10.4.5, determine the wavelength emitted from the transition $n = 4$ to $n = 2$.

12 A simplified energy level diagram for mercury is presented in Worked example 10.4.4. Use this energy level diagram to determine the frequency of light absorbed to excite mercury from the ground state to the $n = 3$ energy level.

13 What is the wavelength of the photons absorbed to excite a ground level hydrogen atom to the $n = 8$ excited state?

14 Determine the frequency of the photons emitted from hydrogen in the transition from the $n = 7$ to the $n = 2$ energy levels.

15 Use the helium ion (He^+) energy level diagram in Figure 10.4.4b to answer this question. A helium ion sample absorbs light with an energy level of 40.9 eV. Determine the transition that occurs.

16 When an electron drops from the $n = 5$ energy level of the hydrogen atom to the $n = 2$ energy level, a 434 nm photon is released. Calculate the energy of the $n = 5$ orbit if the $n = 2$ orbit has an energy of −3.4 eV.

17 A hydrogen discharge tube produces light at a wavelength of 410.2 nm. Determine which transition in hydrogen this corresponds to. Hint: this wavelength is in the visible spectrum and so $n_f = 2$.

18 High school level physics focuses on the spectra of hydrogen, ionised helium and doubly ionised lithium. Evaluate why these three atoms are of particular interest.

Chapter review

10

KEY TERMS

absorption spectra
Compton scattering
continuous spectrum
diffraction
emission spectra
energy level diagram
energy levels
ionisation
single-photon double-slit experiment
standing wave
wave–particle duality

KEY QUESTIONS

Describe

1 Recall which of the following series corresponds to visible light.
- **A** Lyman series
- **B** Balmer series
- **C** Paschen series
- **D** Brackett series

2 Identify which of the following is not a hydrogen-like species.
- **A** H
- **B** Li^{2+}
- **C** Be^{2+}
- **D** He^{+}

3 Which of the following phenomena supports the particle theory of light?
- **A** diffraction
- **B** photoelectric effect
- **C** polarisation of light
- **D** double-slit diffraction

4 White light is shone on a low-pressure gas. The light passing through the gas is analysed. Which of these phenomena can be investigated this way?
- **A** emission spectrum
- **B** absorption spectrum
- **C** speed of light
- **D** photoelectric effect

5 Select the option which most accurately describes the electron orbitals in the Bohr model.
- **A** The electron orbitals have continuous energy values and the energy levels are overlapping.
- **B** The electron orbitals are stable, fixed energy levels and the energy is quantised.
- **C** The electron orbitals' energy levels are randomly distributed.
- **D** The electron orbitals are unstable and the energy levels are variable.

6 Name the lowest energy level of an atom.

7 Describe an electron energy level.

Apply

8 Kaitlyn has a sample of hydrogen gas in the laboratory. The four visible absorption lines of hydrogen are at 410.1 nm, 434.0 nm, 486.1 nm and 656.2 nm. Which of the following energies would not be absorbed?
- **A** 4.847×10^{-19} J
- **B** 4.580×10^{-19} J
- **C** 4.089×10^{-19} J
- **D** 3.561×10^{-19} J

9 Using the energy level diagram for singularly ionised helium in Figure 10.4.4, determine which of the following photon energies will be absorbed by He^{+}.
- **A** 1.8 eV
- **B** 11.2 eV
- **C** 38.3 eV
- **D** 51.0 eV

10 In the helium ion, the radius of a particular electron orbital is 9.50×10^{-10} m. The wavelength of the electron in that orbital is 1.99 nm. Identify from the following options the number of that electron orbital.
- **A** 1
- **B** 2
- **C** 3
- **D** 4

11 Describe the limitations of Rutherford's model of the atom.

12 Explain Bohr's model of the atom and how it addressed the limitations of the Rutherford model of the atom.

13 What is the key difference between Rutherford's and Bohr's models of the atom?

14 Explain why all the frequencies of light above the ionisation energy value for a particular atom are continuously absorbed.

15 State three ways how the particle (photon) model of light is supported by features of the photoelectric effect. Discuss the implications for the wave model of light in each case.

16 Describe how the wave–particle duality of electrons can be used to explain the quantised energy levels of the atoms.

17 A hydrogen atom in the ground state collides with a 10.0 eV photon. Describe the result of such a collision.

Analyse

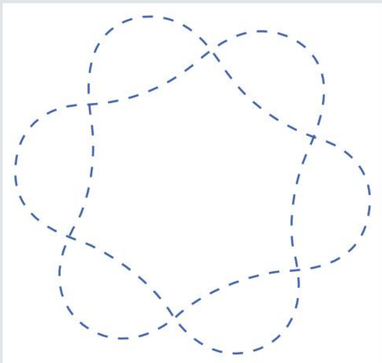
18 Compare Rutherford's and Bohr's models of the atom.

19 Elizabeth and Caroline are using spectroscopes to analyse the light emitted by an incandescent light globe and a sodium vapour lamp. Compare their observations. (You could try this at school.)

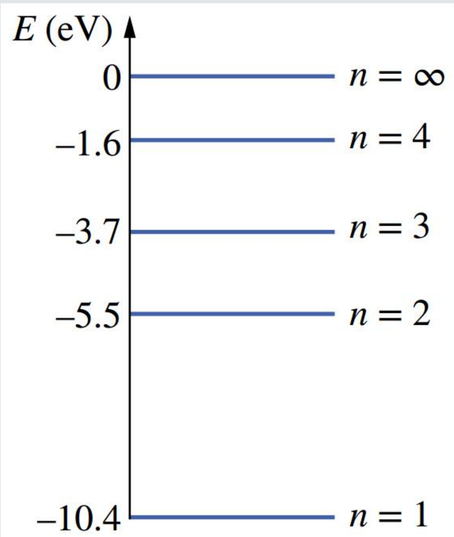
20 Discuss why the gold film needed to be very thin in Rutherford's experiments.

21 Consider how Bohr's model of hydrogen includes light quanta and atomic energy states to explain the specific wavelength observed in the hydrogen spectra.

22 The diagram below represents the 'standing-wave state' of an electron in an atom of hydrogen. Determine the value of n that de Broglie would allocate to this pattern.



Use the energy level diagram for mercury below to answer Questions **23** and **24**.



23 Determine the frequency and wavelength of the light when a mercury atom makes the following transitions:

a $n = 4$ to $n = 1$

b $n = 2$ to $n = 1$

c $n = 4$ to $n = 3$.

24 An electron beam of energy 7.0 eV passes through some mercury vapour in the ground state and excites the electrons to the $n = 3$ energy level.

a List all the possible photon energies that would be present in the emission spectrum when the electrons return from the $n = 3$ energy level to the ground state.

b Determine the shortest wavelength of light present in the emission spectrum.

c A photon collides with a mercury atom in the ground state. As a result, a 30.4 eV electron is ejected from the atom. Calculate the wavelength of the incident photon.

25 Refer to Figure 10.2.1.
Consider electrons that drop back to the ground state from $n = 3$ in sodium.

a Determine how many different photon energies can be produced.

b Calculate the energies, in eV, of the emission transmissions from $n = 3$.

26 A doubly ionised lithium gas sample emits light with a wavelength of 207 nm.

a Determine the energy of the light emitted in eV.

b Determine the transition this light corresponds to. (Refer to the energy level diagram for doubly ionised lithium in Figure 10.4.5).

27 Apply the knowledge that the ground state of hydrogen has an energy of −13.6 eV together with the Rydberg equation to determine the energy of the $n = 7$ energy level of hydrogen.

28 Consider the energy level diagram for the hydrogen atom shown in Figure 10.4.4a. A photon of energy 14.0 eV collided with a hydrogen atom in the ground state.

a Explain why this collision will eject an electron from the atom.

b Calculate the energy of the ejected electron in electron volts and in joules.

c Determine the momentum of the ejected electron.

d Determine the de Broglie wavelength of the ejected electron.

29 A photon with wavelength 640 nm has the same energy as a neutral particle with a velocity of $1.926 \times 10^4\,\mathrm{m\,s^{-1}}$. Determine the mass of the particle.

30 A photon with a momentum of $8.00 \times 10^{-27}\,\mathrm{kg\,m\,s^{-1}}$ was detected from a star. Calculate the temperature of the star (a black body) if this photon was at the maximum wavelength.

31 A metal has a threshold frequency of 1.05×10^{15} Hz. Calculate the momentum of a photon at the threshold frequency.

Interpret

32 Observe the energy level diagrams for hydrogen (Figure 10.4.4a), the helium ion (Figure 10.4.4b) and doubly ionised lithium (Figure 10.4.5). Notice that as the number of the energy level n increases, the energy levels get closer together. Hypothesise why this trend occurs.

33 Determine the energy level transition in hydrogen that produces a photon at 13.517 eV. Remember not all possible energy levels are clearly indicated on the energy level in Figure 10.4.4.

CHAPTER 11

The Standard Model

As an extension from the investigations into nuclear physics that were conducted towards the end of World War II, particle physicists began to predict and discover new subatomic particles. Subatomic particles are those smaller than an atom.

At first, physicists built particle detectors and waited for high-energy cosmic rays from space to smash into their targets in order to see what nuclear fragments they could identify. However, these physicists realised that they would need to build powerful particle accelerators to probe more effectively into the nucleus. Particle accelerators can accelerate protons and electrons to energies high enough to form particles that theoretical physicists had predicted would exist.

These experiments resulted in the discovery of many previously unknown particles and led to the development of the Standard Model of particle physics. The Standard Model is the best description so far of the fundamental building blocks of matter and the forces that govern them. This chapter will explore the particles of the Standard Model, how they interact, and how they make up all known matter.

Syllabus subject matter

Topic 3 • The Standard Model

THE STANDARD MODEL

- Describe the concepts of elementary particles and antiparticles. **11.1**
- Identify the six types of quarks. **11.1, 11.2**
- Describe baryons and mesons. **11.1, 11.2**
- Identify the six types of leptons. **11.2**
- Identify the four gauge bosons. **11.1, 11.3**
- Compare the strong nuclear, weak nuclear and electromagnetic forces in terms of the gauge bosons. **11.3**
- Contrast the fundamental forces experienced by quarks and leptons. **11.3**

PARTICLE INTERACTIONS

- Describe the concepts of lepton number and baryon number. **11.2**
- Solve problems relating to the conservation of lepton number and baryon number in particle interactions using $B = n_b + n_{\bar{b}}$, $B = \frac{1}{3}\left(n_q - n_{\bar{q}}\right)$ and $L = n_l - n_{\bar{l}}$. **11.4**
- Describe electron/electron, electron/positron and neutron decay interactions using particle interaction diagrams. **11.4**
- Describe how symmetry in particle interactions occurs to maintain the principles of conservation. **11.4**

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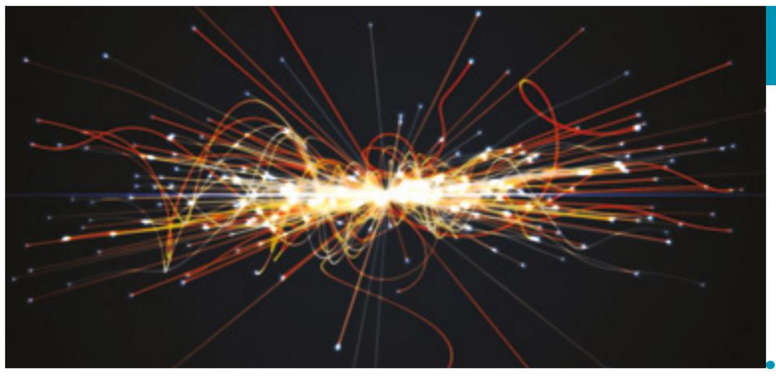
11.1 The Standard Model of particle physics



BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- understand how the Standard Model was developed
- understand the main particles of the Standard Model
- understand that gauge bosons mediate forces between particles
- understand that each matter particle has an antiparticle equivalent.

Currently, the **Standard Model** of particle physics is the most successful theory for predicting the behaviour and properties of the particles that exist in nature. The Standard Model was developed by experimentation and theory together. As technology improved, new particles were discovered, and as the model developed, more particles were predicted and then found. The Standard Model is a mathematical description of all known particles and three of the four forces acting between them.

MATTER PARTICLES

In Chapter 10 you learnt about the development of models of the atom, and how the first subatomic particles were discovered. You will be familiar with the idea that the matter around us, and within us, is made of particles, and that the atoms in your body are comprised of protons, neutrons and electrons (Figure 11.1.1).

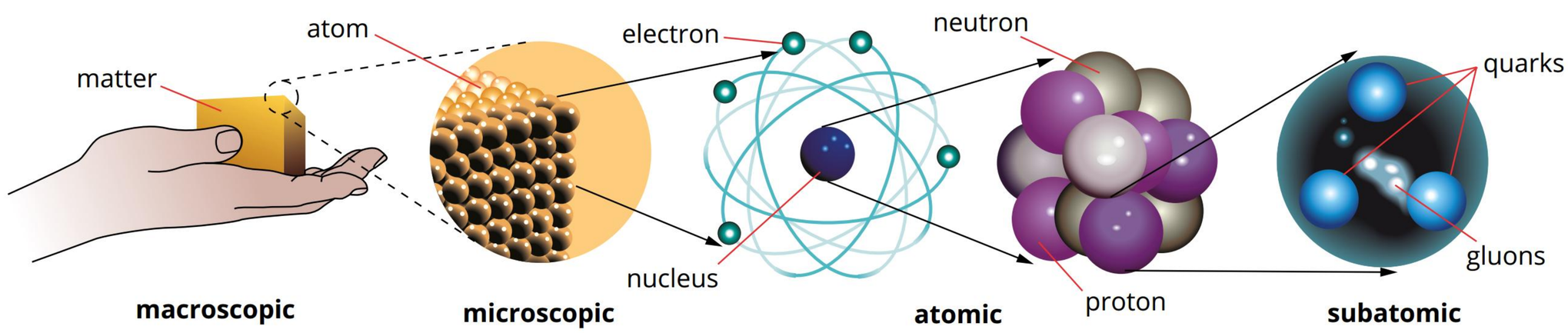


FIGURE 11.1.1 The structure of matter is shown, starting on the left with the macroscopic, and progressing through the microscopic, atomic and subatomic levels.

Since World War II, further research has uncovered about 300 other subatomic particles. Examples include pi-mesons, mu-mesons, kaons, tau leptons and neutrinos. For many years, physicists found it difficult to make sense of this huge array of subatomic particles, once commonly known as the 'particle zoo'. At the time, it was not known that all these particles had an underlying commonality. They were all thought to be fundamental or **elementary particles** and to not be composed of other particles.

Then in 1964, the American physicist Murray Gell-Mann put forward a simple theory. He suggested that most subatomic particles were themselves composed of more fundamental particles called **quarks**. Currently, it is accepted that there are six different quarks, each named for one of its properties: up, down, charm, strange, top and bottom. The latest quark to be identified was the top quark, whose existence was confirmed in 1995.

Subatomic particles that consist of quarks are known as **hadrons**. Quarks are always found bound together to make hadrons; they are not found alone, but they combine to form hundreds of different particles. These particles come in two types: **baryons**, which are made of three quarks, and **mesons**, which are made of a quark and an antiquark (called a quark–antiquark pair). Protons and neutrons are baryons.

Protons consist of two up quarks and one down quark, and neutrons consist of one up quark and two down quarks. Baryons and mesons interact via the **strong nuclear force**—the same force that binds together protons and neutrons in a nucleus.

Electrons belong to another group of particles called **leptons**. This group has six members: electron, electron-neutrino, muon, muon-neutrino, tau and tau-neutrino. Leptons are fundamental particles; they are not composed of quarks, and they interact via the **weak nuclear force**. Quarks and leptons are part of a group of particles that makes up all matter: **fermions**.

> The Standard Model states that all particles of matter are made of one or more of the 12 fundamental or elementary particles (six quarks and six leptons) and their antimatter opposites. An elementary particle is one that, to the best of scientific knowledge, is not comprised of other smaller particles.

Force particles

There is another type of particle in the Standard Model: the particles that mediate interactions between other particles (in other words, they transmit the force between particles). These are called **gauge bosons**, and they describe three of the four fundamental forces in nature:

- the **photon**, which mediates the electromagnetic force
- the **gluon**, which mediates the strong nuclear force
- the $\mathbf{W^+}$, $\mathbf{W^-}$ and $\mathbf{Z^0}$ particles, which mediate the weak nuclear force.

A theoretical particle called the graviton has been predicted to mediate the gravitational force, but it has not yet been found, and is not included in the Standard Model. Figure 11.1.2 illustrates how the known particles are classified under the Standard Model.

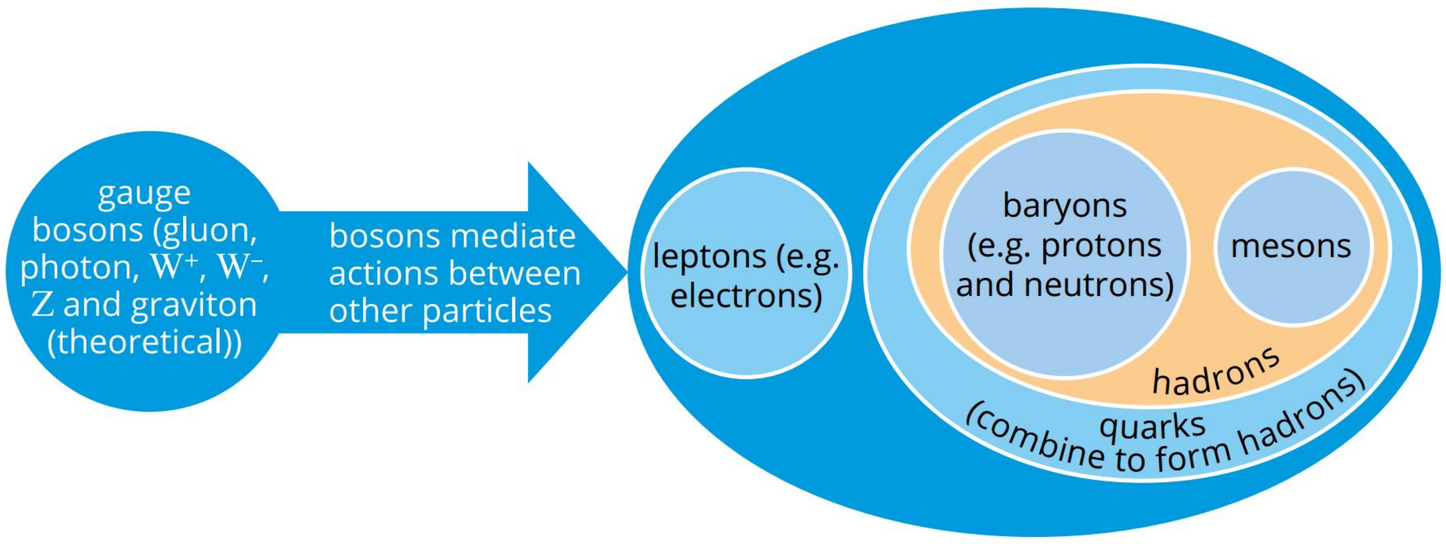


FIGURE 11.1.2 This diagram shows the different groups of elementary and composite particles.

Matter and antimatter

The British theoretical physicist Paul Dirac developed a set of equations that enabled him to make predictions about electrons travelling close to the speed of light. His equations combined the wave equations of quantum mechanics with aspects of general relativity. From these equations, Dirac predicted the existence of several phenomena, including a particle similar to an electron with a positive charge, which is now known as the positron. He went on to predict the existence of antimatter particles for all particles. This prediction was confirmed by experiment by Carl Anderson in 1932.

Dirac predicted that particles have what is called an **antiparticle**. Recall from Unit 1 that beta decay can be either beta negative, when an electron is emitted from a nucleus, or beta positive, when a positron is emitted. The positron is the antiparticle of the electron. It has the same properties of mass, charge and lifespan as the electron, but its electric charge and **quantum numbers** (which will be covered in the rest of this chapter) are the same in magnitude but have the opposite sign. This is true for all particles and their antiparticles.

Antiparticles have the same properties of mass, charge and lifespan as their corresponding matter particle, but have electric charge and quantum numbers of opposite sign.

When including antiparticles in equations or diagrams, two conventions are used.

- The antiparticle of some particles (including quarks and uncharged leptons) is indicated by placing a bar above the symbol for the normal matter particle. For example, the antiparticle of the electron neutrino (ν_e) is the electron antineutrino ($\bar{\nu}_e$); the antiparticle of the up quark (u) is the antiup quark ($\bar{u}$).
- The antiparticles of some charged particles are given the symbol of the particle but with the opposite sign; for example, the antiparticle of the muon (μ^-) is the antimuon (μ^+).

11.1 Review

SUMMARY

- The Standard Model of particle physics is the best model physicists have to explain the behaviour of matter and the forces that act on matter.
- The Standard Model of particle physics explains three of the four fundamental forces in the universe (electromagnetism, the strong nuclear force and the weak nuclear force). These forces are mediated by particles called gauge bosons.
- All particles of matter are made of one or more of the 12 fundamental particles (six quarks and six leptons) and their antimatter opposites.
  - Quarks combine to form hadrons and cannot exist alone. The hadrons include baryons (made of three quarks) and mesons (made of a quark–antiquark pair).
  - Leptons are fundamental particles and include the electron.
- Gauge bosons are particles that mediate forces between other particles. They are the photon, which mediates the electromagnetic force, the gluon, which mediates the strong nuclear force, and the W^+, W^- and Z^0 particles, which mediate the weak nuclear force.
- All matter particles have a corresponding antiparticle. Antiparticles have the same properties of mass, charge and lifespan as their corresponding matter particle, but have electric charge and quantum numbers of opposite sign.

KEY QUESTIONS

Describe

1 The Standard Model of particle physics explains three of the four fundamental forces in the universe. State which force it does not explain.

2 Refer to the Standard Model of particle physics. State the name that is given to:

a force-mediating particles

b the two types of fundamental particles that make up matter.

3 Electrons are fundamental particles that interact via the weak nuclear force. State what group of particles electrons belong to.

4 Recall the antimatter particle of the electron.

5 What kind of particle is a proton?

6 What type of particles make up mesons?

7 How many quarks make up a baryon?

Apply

8 Explain the properties of antimatter particles.

9 Lee is explaining the concept of antimatter to his brother and states that neutrons are the antimatter particle equivalent of protons, because they are similar in mass but have different properties. Explain whether he is correct.

Analyse

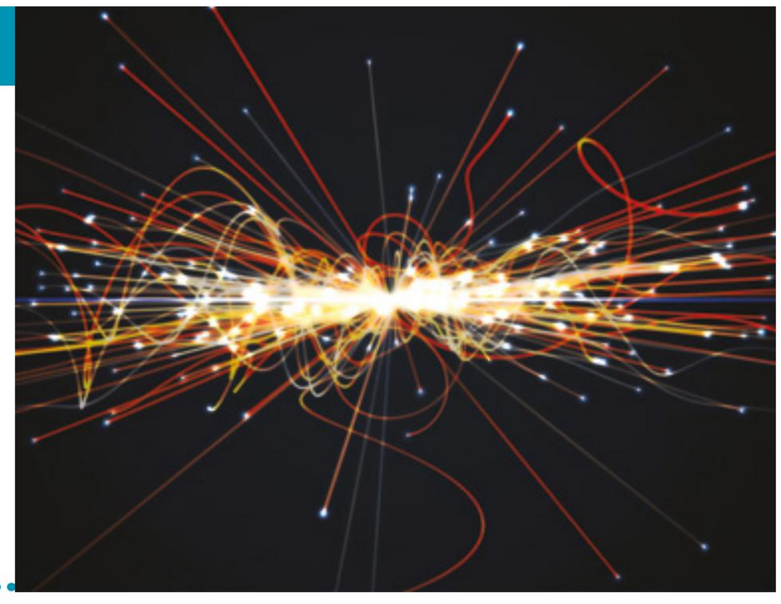
10 In the 1990s physicists first created anti-hydrogen. Identify the particles that would be needed to create a single antihydrogen atom, given that hydrogen consists of a single electron in a bound state around a single proton.

11 There is an experiment at CERN's antimatter factory called ALPHA-g where they are dropping anti-hydrogen to confirm its behaviour due to gravity. Would scientists expect antimatter to fall the same as matter due to gravity? Justify your answer.

11.2 Quarks and leptons

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- understand the difference between baryons and mesons, and how they are made up of six different flavours of quark
- understand baryon number and colour charge
- understand how the electromagnetic charges of individual quarks combine to make up the electromagnetic charge of a particle
- understand that leptons are fundamental particles that interact via the weak nuclear force, and are not made of quarks
- understand the six types of leptons and their properties.



Quarks and leptons are elementary particles and together make up all matter, known as fermions. The behaviour and properties of quarks and leptons are quite different from one another. Different key quantum numbers are used to describe quarks and leptons, and are governed by different conservation laws.

QUARKS

As you have seen in Module 11.1, protons and neutrons, in the group of particles called hadrons in the Standard Model, are made of even smaller particles called quarks. So far, quarks have only been found as part of larger particles; they have not been found alone. It is thought that they may have existed alone in the very energetic first fractions of a second of the early universe. Quarks, and the particles they make up, interact via the strong nuclear force (the same force that binds together protons and neutrons in a nucleus, as seen in Unit 1). Quarks also interact via the weak nuclear force and the electromagnetic force.

Quarks have a series of properties that govern how they behave and how they combine to form particles. For this course, you don't need to memorise the different properties of the quarks that make up each particle, but you do need to understand the basics of how quarks combine (Figure 11.2.1).

As explained in the previous module, there are six different types of quarks, which are referred to as the six 'flavours' of quarks. These are:

- up (u)
- down (d)
- strange (s)
- charm (c)
- bottom (b)
- top (t).

Just as electrons have an antimatter particle—the positron—quarks also have antiparticles called antiquarks, which have the same quantum numbers but with the opposite sign. The antiquark of the up quark is antiup, not the down quark, and the antiquark of the top quark is the antitop, not the bottom quark. An antiquark has the same symbol as its corresponding quark, but with a line above it: for example, up (u) and antiup ($\bar{u}$). Quarks have the properties of **baryon number** and charge, which must add together to give the total baryon number and charge of the particles that they combine to make (Figure 11.2.2).

The charge of particles and ions is compared to the charge on a proton ($+e = +1.6 \times 10^{-19}$ C), so that a proton has a charge of +1 and an electron has a charge of −1. Quarks have non-integer charge; their charge is a fraction (one-third or two-thirds) of the charge on a proton. Leptons have electromagnetic charges of −1 or 0 multiples of 1.6×10^{-19} C.

Quarks are fundamental particles. They come in six flavours: up (u), down (d), strange (s), charm (c), bottom (b) and top (t), and interact via the strong and weak nuclear forces and the electromagnetic force.

Whether the word 'quark' is pronounced to rhyme with 'stork' or 'bark' is a matter of debate. The name comes from the line 'Three quarks for Muster Mark!', from the book *Finnegan's Wake* by James Joyce.

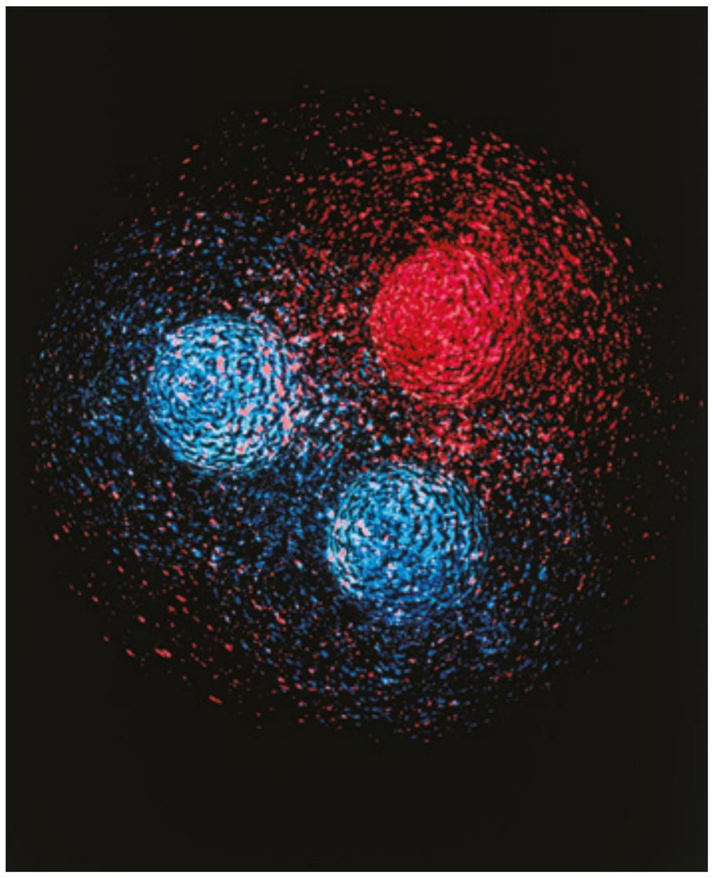


FIGURE 11.2.1 An artist's representation of the three quarks that make up a proton

Figure 11.2.2 shows the properties of the six types of quark and six types of antiquark.

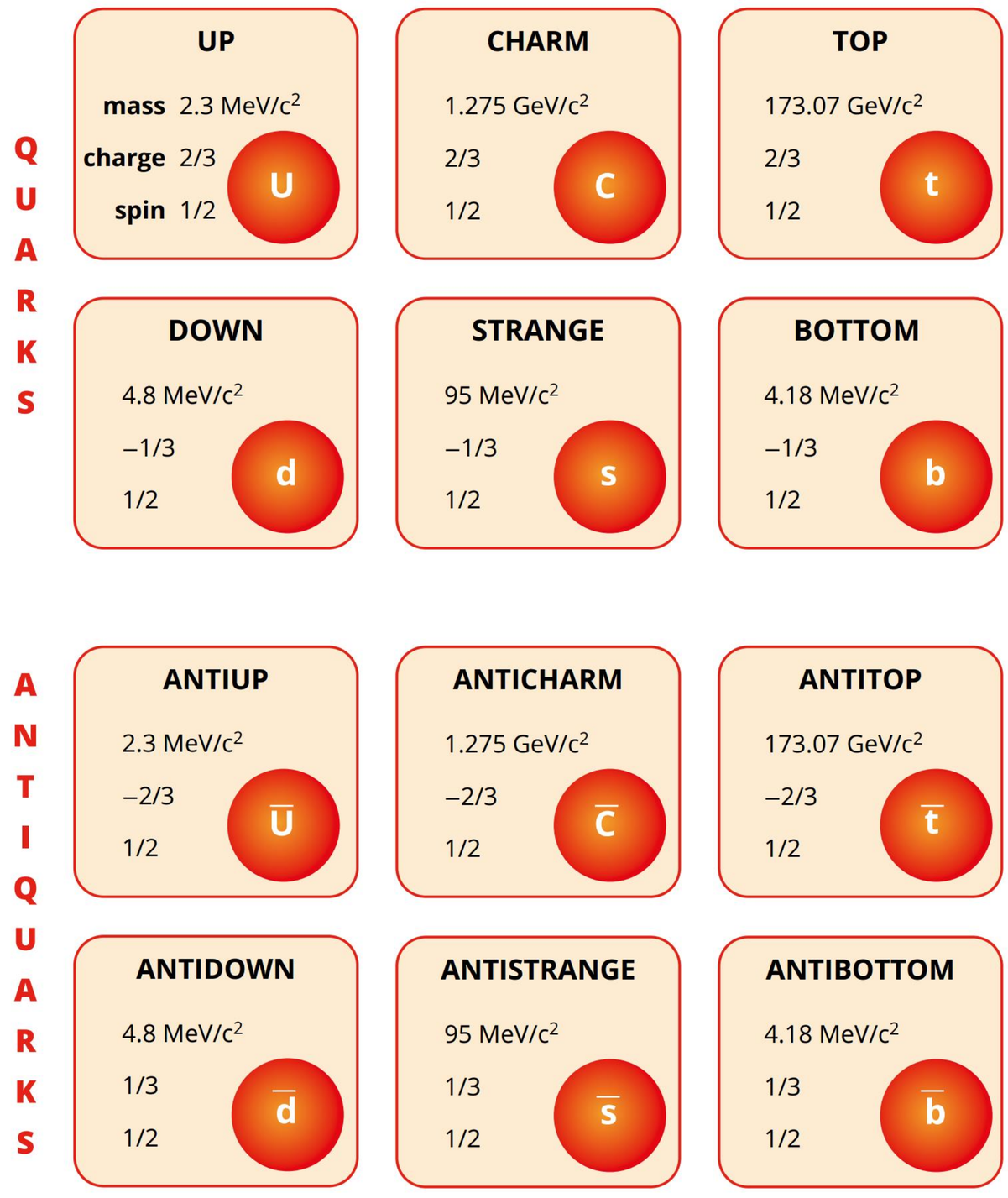


FIGURE 11.2.2 The six flavours of quarks, their antiquarks and some of their properties

All of these different properties might suggest that quarks could combine in thousands of ways to form thousands of different particles. However, there are rules for how quarks combine that limit the number of particles they can form, as will be shown in the next section.

TYPES OF HADRONS

Recall from Module 11.1 that hadrons are particles that are made of quarks. Hadrons are further categorised into two groups, the baryons and the mesons. These are separated according to how many quarks they contain, and a property called baryon number.

Baryons

Baryons consist of three quarks, and include protons (uud) and neutrons (udd).

Baryons are a type of hadron made of three quarks. Examples of baryons include the proton (two up quarks and one down quark, or uud) and the neutron (one up quark and two down quarks, or udd). This group of particles also includes the antiproton ($\overline{p}$) and the antineutron ($\overline{n}$), as well as hundreds of other particles of the particle zoo and their antiparticles, such as lambda-zero (Λ^0) and antilambda-zero ($\overline{\Lambda}^0$), sigma-plus (Σ^+), sigma-zero (Σ^0) and sigma-minus (Σ^-), xi-zero (Ξ^0) and omega-minus (Ω^-).

Quarks also have a property called **colour charge**. Colour charge comes in three different types: red, green and blue for quarks, and antired, antiblue and antigreen for antiquarks. Each quark in a particle must have a different colour charge. These must always combine to give a total colour charge of 'white', in the same way that adding red, green and blue light will make white light. For example, baryons such

as the proton and neutron consist of three quarks, and they must have one red, one green and one blue charged quark (Figure 11.2.3a).

Baryon antiparticles must have one antired, one antigreen and one antiblue charged antiquarks.

Colour charge is a useful way to remember why there are never any 'free' individual quarks by themselves.

Note that the quarks are not actually these colours; these are names given to properties of quarks to help model their properties.

The quarks in a proton must also combine to have the total electromagnetic charge of the proton, which is one 'fundamental charge' ($+e$ or $+1.6 \times 10^{-19}$ C). Therefore, quarks must have an electromagnetic charge that is less than the fundamental unit. In fact, quarks have an electromagnetic charge of either $+\frac{2}{3}e$ (up, charm and top) or $-\frac{1}{3}e$ (down, strange and bottom).

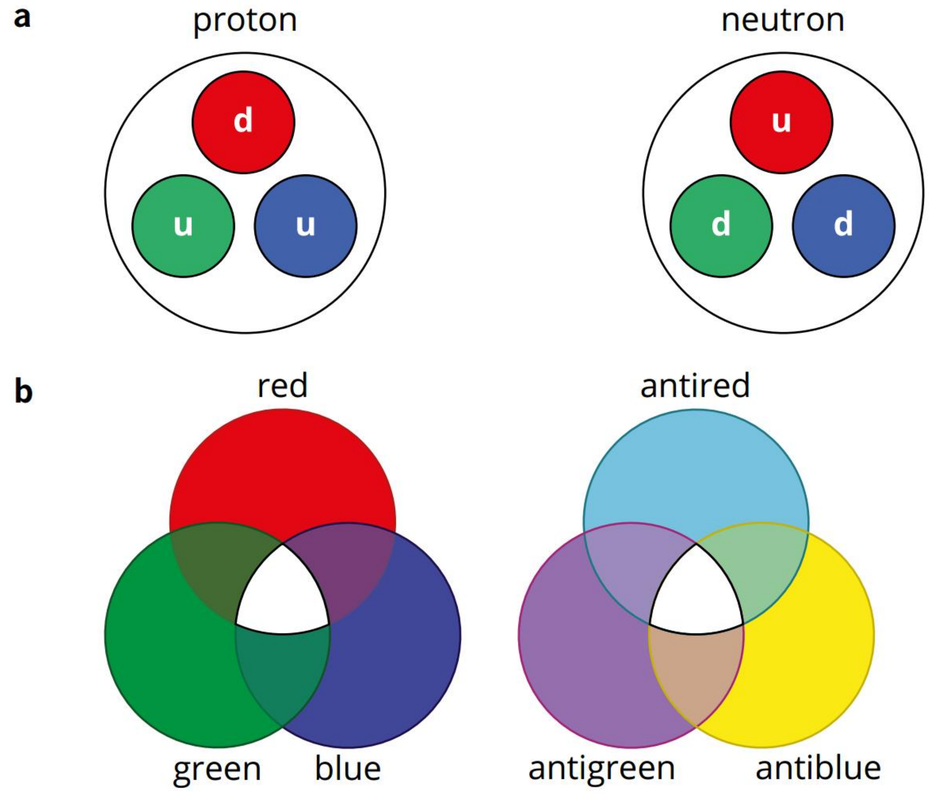


FIGURE 11.2.3 (a) The proton and neutron are both baryons, which are made of three quarks. Each quark in a baryon has a different colour charge. (b) The colour charge of quarks in a particle or antiparticle combines to make white.

The electromagnetic charge of a proton (uud) is, therefore, made up of:

$$\left(+\frac{2}{3}e\right)+\left(+\frac{2}{3}e\right)+\left(-\frac{1}{3}e\right)=\left(+\frac{3}{3}e\right)=+1e$$

A neutron is made up of an up quark and two down quarks (udd) of different colours, which equates to an electromagnetic charge of:

$$\left(+\frac{2}{3}e\right)+\left(-\frac{1}{3}e\right)+\left(-\frac{1}{3}e\right)=0$$

Worked example 11.2.1

ELECTROMAGNETIC AND COLOUR CHARGE IN BARYONS

a The lambda particle, Λ^0, is made of one up, one down and one strange quark (uds). Using the properties of quarks given in Figure 11.2.2 (page 290), demonstrate that the electromagnetic charge of the Λ^0 particle is zero.

Thinking	Working
State the electromagnetic charges of the individual quarks that make up the lambda particle.	The electromagnetic charges of the quarks are: $u = +\frac{2}{3}e$ $d = -\frac{1}{3}e$ $s = -\frac{1}{3}e$
Add the charges to find the charge on the particle.	$\left(+\frac{2}{3}e\right)+\left(-\frac{1}{3}e\right)+\left(-\frac{1}{3}e\right)=0$

b A particular lambda-plus particle, Λ^+, is found to contain one green up quark, one blue down quark and one other unknown quark. The Λ^+ has an electromagnetic charge of $+1e$. Use the properties of quarks given in Figure 11.2.2 to determine the electromagnetic charge and colour charge of the other quark, and suggest the type of quark it could be.

Thinking	Working
State the electromagnetic charges of the known quarks that make up the lambda-plus particle and the electromagnetic charge of the lambda-plus particle.	The electromagnetic charges of the quarks and Λ^+ are: $u = +\frac{2}{3}e$ $d = -\frac{1}{3}e$ $\Lambda^+ = +1e$
Find the charge on the third quark.	$1-\left(+\frac{2}{3}e\right)-\left(-\frac{1}{3}e\right)=\left(+\frac{2}{3}e\right)$
Find the colour charge of the third quark.	The third quark must be red since the total colour must be white and the green and blue colour charges are already given.
Use Figure 11.2.2 to identify the types of quark it could be.	Quarks with a $+\frac{2}{3}e$ charge are up, charm and top. (In fact, it is a charm quark, and the Λ^+ is udc.)

➤ Try yourself 11.2.1

ELECTROMAGNETIC AND COLOUR CHARGE IN BARYONS

a The sigma-minus particle, Σ^-, is made of two down quarks and one strange quark (dds). Use the properties of quarks given in Figure 11.2.2 to demonstrate that the electromagnetic charge of the Σ^- particle is $-1e$.

b A particular sigma-zero particle, Σ^0, is found to contain one red up quark, one green down quark and one other unknown quark. The Σ^0 has an electromagnetic charge of zero. Use the properties of quarks given in Table 11.2.1 to determine the electromagnetic charge and colour charge of the other quark, and suggest what types of quark it could be.

Table 11.2.1 gives a summary of some baryons and their constituent quarks. It also shows baryon number. The baryon number of each quark is $+\frac{1}{3}$, so the three quarks that make up a baryon add to give a baryon number of +1. Antiquarks have a baryon number of $-\frac{1}{3}$, so three antiquarks together have a baryon number of −1.

Mesons

The other type of hadron is the meson. Mesons are unstable, short-lived particles, with lifetimes of billionths of a second or less. Due to their short lifetime, they are harder to study than baryons such as protons and neutrons. In this group are many particles and their antimatter particles, such as the pion (π^+), antipion (π^-) and pi-zero (π^0), the kaon (K^+) and antikaon (K^-), and the eta (η^0). (The antimatter particle of the eta is considered to be itself. Understanding this is beyond the scope of this course.) Table 11.2.2 shows some of the many mesons and their constituent quarks.

TABLE 11.2.1 Baryons and their constituent quarks

Baryon name	Symbol	Baryon number (B)	Quarks
proton	p	+1	uud
antiproton	$\bar{p}$	−1	$\bar{u}\bar{u}\bar{d}$
neutron	n	+1	udd
antineutron	$\bar{n}$	−1	$\bar{u}\bar{d}\bar{d}$
lambda-plus	Λ^+	+1	udc
lambda-zero	Λ^0	+1	uds
sigma-plus	Σ^+	+1	uus
sigma-zero	Σ^0	+1	uds
sigma-minus	Σ^-	+1	dds
xi-zero	Ξ^0	+1	uss
xi-plus	Ξ^+	+1	dss
omega-minus	Ω^-	+1	sss

TABLE 11.2.2 Various mesons and their constituent quarks.

Meson name	Symbol	Baryon number (B)	Quarks
pion-plus	π^+	0	$u\bar{d}$
pion-minus	π^-	0	$\bar{u}d$
kaon-plus	K^+	0	$u\bar{s}$
kaon-minus	K^-	0	$\bar{u}d$
rho-plus	ρ^+	0	$u\bar{d}$
rho-minus	ρ^-	0	$\bar{u}d$
phi	ϕ	0	$\bar{s}s$
D-plus	D^+	0	$c\bar{d}$
D-zero	D^0	0	$c\bar{u}$
D-plus-s	Ds^+	0	$c\bar{s}$
B-minus	B^-	0	$b\bar{u}$
upsilon	Υ	0	$b\bar{b}$

Mesons are made of two quarks: a quark and an antiquark, called a quark–antiquark pair. For example, the pion-plus (π^+) consists of an up quark and an antidown quark ($u\bar{d}$) (Figure 11.2.4). Each quark has a colour charge, and, like baryons, their colour charges must add up to 'white'; for example:

- red + antired
- blue + antiblue
- green + antigreen.

As for baryons, the electromagnetic charges of the quarks in a meson add to give the total charge of the particle they make up. For example, the electromagnetic charge of the pion-plus ($u\bar{d}$) is $\left(+\frac{2}{3}e\right)+\left(+\frac{1}{3}e\right)=\left(+\frac{3}{3}e\right)=+1e$.

Mesons consist of two quarks: a quark–antiquark pair.

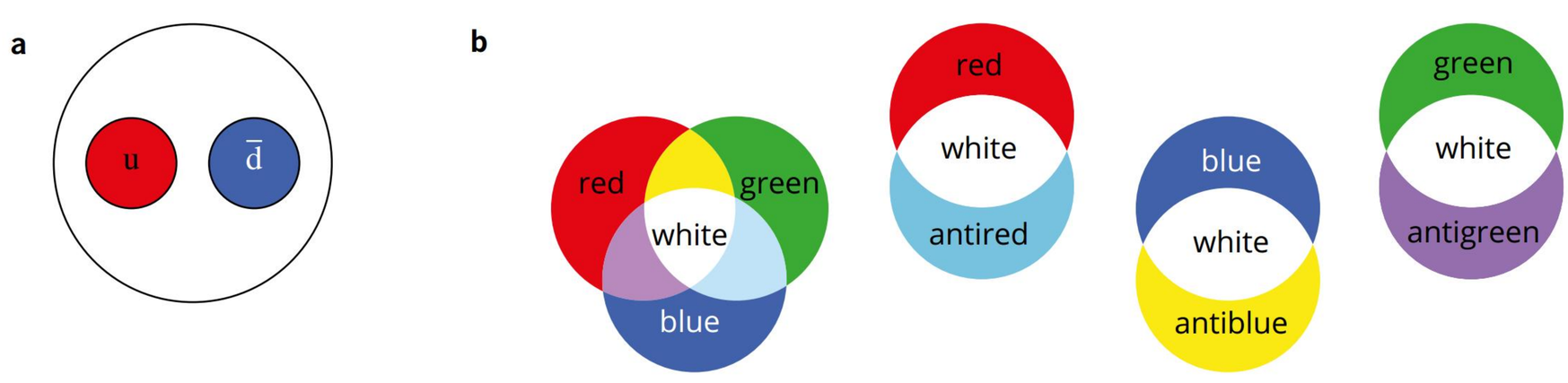


FIGURE 11.2.4 (a) The pion-plus (π^+) meson consists of an up quark and an antidown quark ($u\bar{d}$). (b) Baryons always have red, green and blue colour charge combinations, as shown on the left. Mesons always have a colour–anticolour charge, as shown in the other three diagrams.

BARYON NUMBER

Baryon number is a quantity that indicates if a particle is baryon or not. It is determined by the number of quarks and antiquarks that make up the particle.

The baryon number of a baryon is one, an antibaryon minus one and a meson is zero. You can think of the baryon number as indicating whether a particle is a baryon (1) or not (0). There is no corresponding quantity called a meson number.

$$B = \frac{1}{3}\left(n_q - n_{\bar{q}}\right)$$

where

B is the baryon number of the particle

n_q is the number of quarks in the particle

$n_{\bar{q}}$ is the number of antiquarks in the particle

Worked example 11.2.2

BARYON NUMBER FOR BARYONS AND MESONS

Determine the baryon number for:

a a proton

Thinking	Working
Count the number of quarks and antiquarks in the particle.	The proton is uud Number of quarks: $n_q = 3$ Number of antiquarks: $n_{\bar{q}} = 0$
Calculate the baryon number using: $B = \frac{1}{3}\left(n_q - n_{\bar{q}}\right)$	$B = \frac{1}{3}\left(n_q - n_{\bar{q}}\right)$ $= \frac{1}{3}(3-0)$ $= \frac{1}{3} \times 3$ $= 1$

b a pion-plus particle $\left(u\bar{d}\right)$

Count the number of quarks and antiquarks in the particle.	The pion-plus particle is $u\bar{d}$ Number of quarks: $n_q = 1$ Number of antiquarks: $n_{\bar{q}} = 1$
Calculate the baryon number using: $B = \frac{1}{3}\left(n_q - n_{\bar{q}}\right)$	$B = \frac{1}{3}\left(n_q - n_{\bar{q}}\right)$ $= \frac{1}{3}(1-1)$ $= \frac{1}{3} \times 0$ $= 0$

➤ Try yourself 11.2.2

BARYON NUMBER FOR BARYONS AND MESONS

Determine the baryon number for:

a an antiproton

b a D-plus particle $(c\bar{d})$.

LEPTONS

The other group of matter particles, apart from hadrons, are leptons. The particles in this group interact by the weak nuclear force. Leptons that carry an electromagnetic charge can also interact via the electromagnetic force. Leptons do not interact via the strong nuclear force as quarks and hadrons do, and they are fundamental particles; they are not made up of smaller particles. Leptons do not carry a colour charge.

The leptons you will be most familiar with are the electron and the electron neutrino, but the group also includes the muon and tau particles, as well as their corresponding neutrinos, and their antimatter opposites. Recall from Chapter 8 that particles called muons could reach the surface of Earth before they decayed because of time dilation and length contraction.

Leptons are thought to come in only six types: electrons (e^-), muons (μ^-) and tau (τ^-), and their corresponding neutrinos—the electron neutrino (ν_e), muon neutrino (ν_μ) and tau neutrino (ν_τ). Each of these six particles has a corresponding antimatter particle: the positron, electron antineutrino, antimuon, muon antineutrino, antitau and tau antineutrino.

Recall from Unit 1 that an electron ejected from the nucleus in a beta negative decay is always emitted with an antineutrino. In a beta positive decay, an antimatter positron is emitted with a neutrino.

Neutrinos have a very small mass compared to an electron, and they interact so weakly with other matter that they can go through the entire Earth in the way that photons (light) go through a pane of glass. As neutrinos have zero charge, they do not experience the electromagnetic force. Another lepton particle, the muon (μ^-), can also be emitted from the nucleus along with the muon antineutrino ($\bar{\nu}_\mu$) in a way similar to the beta particle. Muons are very similar to electrons, but 207 times larger, and do not make up everyday matter.

Leptons have electron, muon and tau **lepton numbers**. These are the equivalent of the baryon number for hadrons. An electron has an electron lepton number of +1, a muon lepton number of 0 and a tau lepton number of 0. An electron neutrino has an electron lepton number of +1, a muon lepton number of 0, and a tau lepton number of 0, and so on. The antimatter equivalents have negative lepton numbers; the positron and electron antineutrino both have an electron lepton number of −1, and so on. Lepton numbers help to explain why particles decay in the way they do. This will be discussed in Module 11.4.

Figure 11.2.5 is a summary of leptons and their properties.

Leptons are fundamental particles, and interact via the weak nuclear force. They include the electron, muon and electron neutrino.

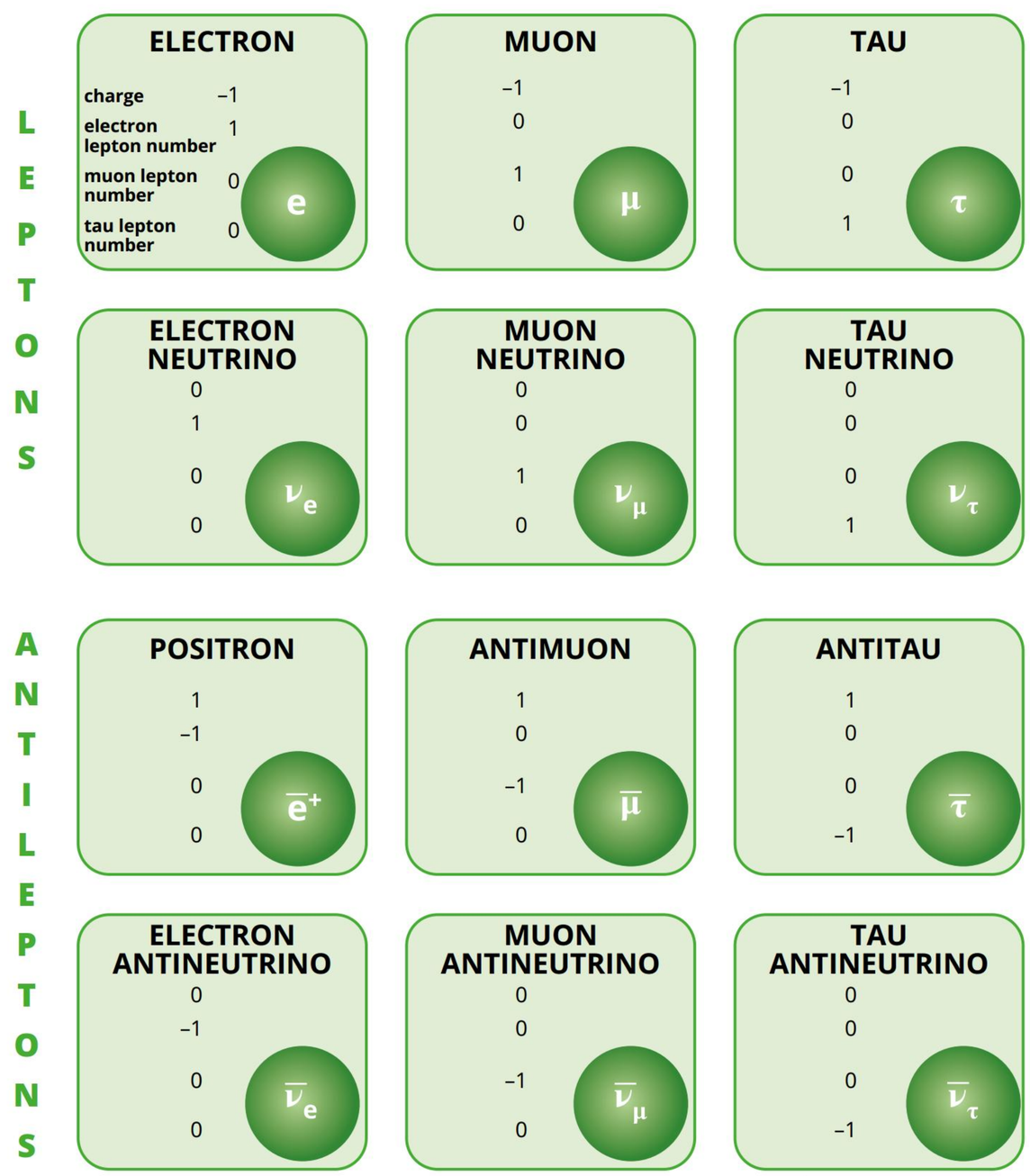


FIGURE 11.2.5 The six leptons, their antiparticles and some of their properties

Table 11.2.3 and Figure 11.2.6 is a summary of the fundamental particles that make up matter, and some of their properties.

TABLE 11.2.3 A summary of the fundamental particles and their properties

Particle type	Quark	Lepton
particles	up (u) down (d) charm (c) strange (s) top (t) bottom (b)	electron (e) electron neutrino (ν_e) muon (μ) muon neutrino (ν_μ) tau (τ) tau neutrino (ν_τ)
antiparticles	antiup ($\bar{u}$) antidown ($\bar{d}$) anticharm ($\bar{c}$) antistrange ($\bar{s}$) antitop ($\bar{t}$) antibottom ($\bar{b}$)	positron (e^+) electron antineutrino ($\bar{\nu}_e$) antimuon (μ^+) muon antineutrino ($\bar{\nu}_\mu$) antitau (τ^+) tau antineutrino ($\bar{\nu}_\tau$)
interacts via	strong nuclear force, weak nuclear force and electromagnetic force	weak nuclear force and the charged leptons also via the electromagnetic force
exists alone?	no, is always part of a larger particle	yes
makes up	hadrons, split into: mesons (quark + antiquark) baryons (three quarks or three antiquarks)	–

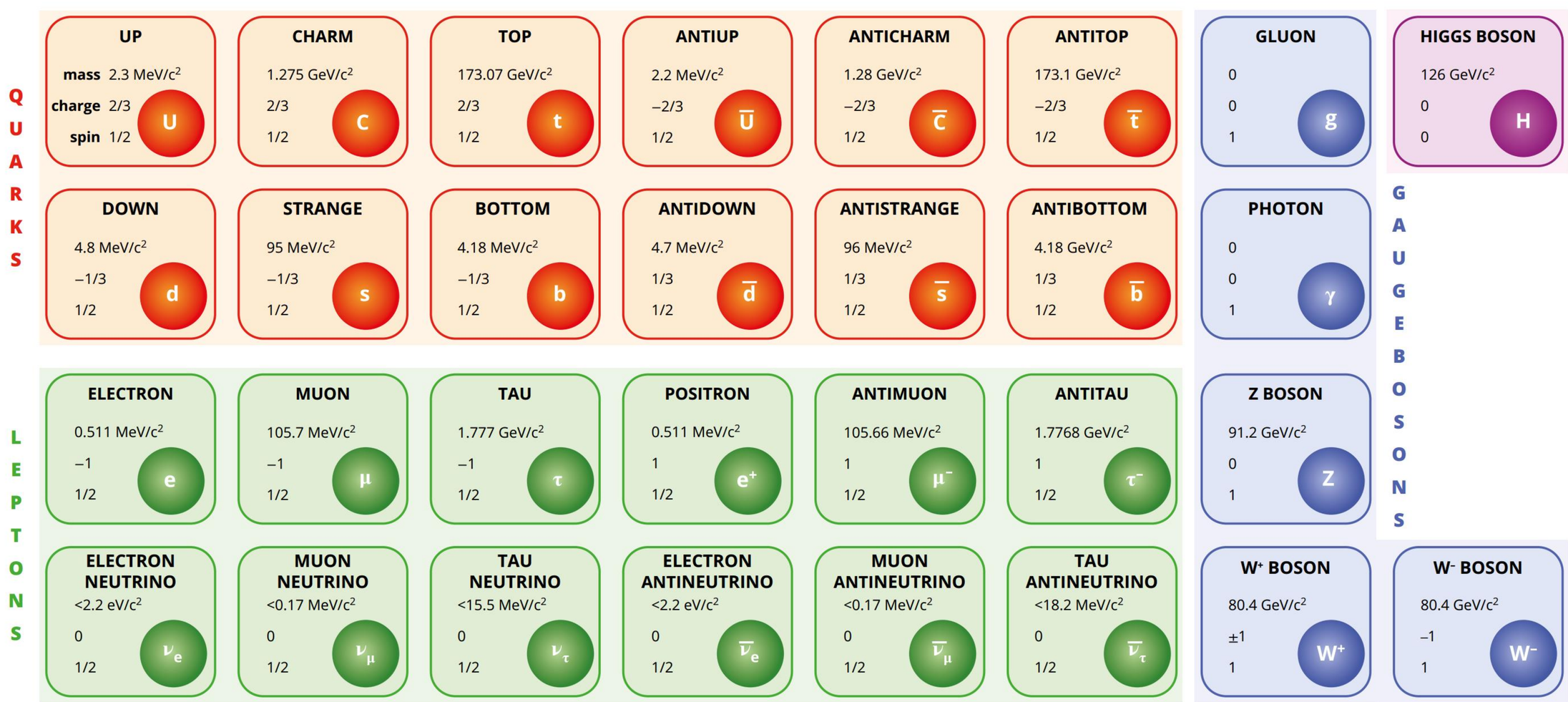


FIGURE 11.2.6 All the fundamental particles including the quarks, leptons and bosons

11.2 Review

SUMMARY

- Quarks are fundamental particles and interact via the strong nuclear force, the weak nuclear force and the electromagnetic force.
- There are six flavours of quark: up, down, strange, charm, top and bottom.
- Quarks combine to make up hadrons, which are subdivided into baryons and mesons.
- Baryons contain three quarks or three antiquarks, and have a baryon number of 1 for matter, and –1 for antimatter.
- Mesons consist of a quark–antiquark pair and have a baryon number of 0.
- Quarks have a property called colour charge, which can be red, green or blue (or antired, antigreen or antiblue). The colour charge of baryons and mesons must always be white: either red + green + blue or antired + antigreen + antiblue for baryons, and red + antired, blue + antiblue or green + antigreen for mesons.
- Quarks also have electromagnetic charge, which adds to give the charge of the particle.
- Leptons are fundamental particles and interact via the weak nuclear force. They also interact via the electromagnetic force if they carry charge.
- The group of leptons consists of six particles: the electron, the muon and the tau, and their neutrinos.
- Each of these leptons has a corresponding antimatter particle.
- Leptons have a property called the lepton number, which helps explain why subatomic particles decay in the way they do.

KEY QUESTIONS

Describe

1 State two ways in which leptons differ from hadrons.

2 Identify the six flavours of quarks.

3 Recall the quarks that make up:

a a proton

b a neutron

d an antiproton.

4 State the three forces that quarks can experience.

5 State the six types of leptons and their antimatter particle equivalents.

6 State the two forces that leptons can experience.

Apply

7 Explain, with reference to colour charge, why quarks do not exist on their own.

8 Describe the difference between baryons and mesons, with reference to their constituent quarks and baryon number.

9 Explain the difference between the electromagnetic charge on lepton particles (e.g. the electron), on neutrinos and on lepton antiparticles.

10 Determine the brayon number (for the given the quark composition) of:

a a neutron (udd)

b a sigma-zero (uds)

c an upsilon $(b\bar{b})$.

11 A particular phi particle $(s\bar{s})$ consists of a red strange quark and what colour charge antistrange quark?

Analyse

12 Determine why a proton is a baryon, but a pion-plus is not $(u\bar{d})$. Refer to the baryon numbers of their constituent quarks.

13 If the up, charm and top quarks have an electromagnetic charge of $+\frac{2}{3}e$ and the down, strange and bottom quarks have an electromagnetic charge of $-\frac{1}{3}e$, and antiquarks have an electromagnetic charge that is equal but of opposite sign, calculate the electromagnetic charge (for the given the quark composition) on:

a a proton (uud)

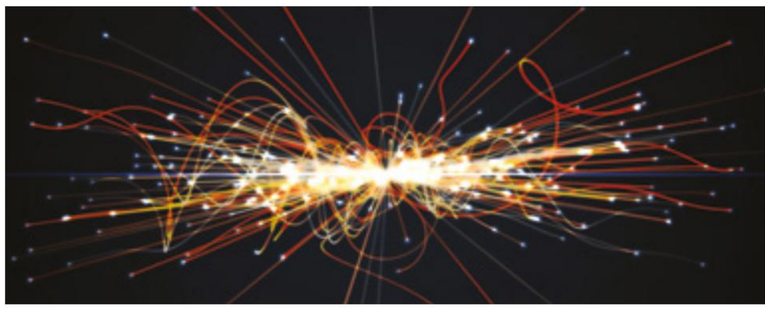
b a neutron (udd)

c a kaon-plus $(u\bar{s})$.

14 George and Johannah are arguing over antimatter particles. George says that the antiparticle of an antiproton is a proton, while Johannah says that the antiparticle of an antiproton is a positron. Determine who is correct and explain why with reference to its constituent quarks.

15 Explain why certain mesons, for example upsilon $(b\bar{b})$ are considered to be anti-particles of themselves.

11.3 Gauge bosons



BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- understand how forces can be thought of in terms of the exchange of particles called gauge bosons
- understand which gauge boson mediates which force.

In the previous modules of this chapter, you learnt about three of the four fundamental forces that can act between particles and which govern their behaviour:

- the strong nuclear force
- the electromagnetic force
- the weak nuclear force.

Each of these forces has a different strength and acts over different distances. For example, the strong nuclear force, which acts on quarks (and the particles made of quarks, such as protons and neutrons), acts over very short distances (i.e. on the subatomic scale), but is very large. Like gravity, the electromagnetic force acts over an infinite range, but is much stronger than gravity and much weaker than the strong nuclear force. The weak nuclear force is stronger than gravity but is weaker than the electromagnetic and strong nuclear forces.

One of the fundamental assumptions of the Standard Model is that these forces arise through the exchange of particles called gauge bosons. Bosons are often called force-carrying, force-mediating or exchange particles. (Note that *gauge* bosons are commonly referred to as bosons; however, gauge bosons are a subgroup of the larger boson group of particles with their own distinct properties. This larger boson group includes the famous Higgs boson, which interacts with particles to give them mass.)

Each force has its own boson. According to the notion of wave–particle duality, each of these forces can be considered as particles. (Wave–particle duality was described in detail in Chapters 9 and 10.)

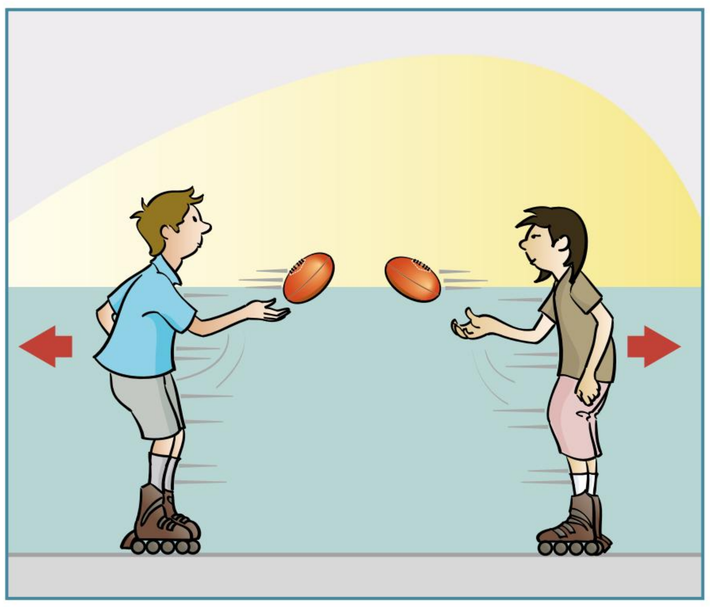


FIGURE 11.3.1 Inline skaters exchanging footballs act as an analogy for particles experiencing repulsive forces due to the exchange of gauge bosons.

FORCES THROUGH EXCHANGE OF PARTICLES

Previously, forces were thought of as being exerted on particles by fields. For example, you have seen in your studies of physics that there is a region around a charged particle where another charged particle experiences a force. This may seem quite puzzling as the force is applied without any direct interaction by the two particles. The same effect is felt when two magnets are brought together. The magnets do not need to touch in order to feel the force between them. In the Standard Model this puzzlement is resolved, as forces are thought to be exerted through the exchange of other particles.

To use an analogy to see how a force can be exerted on two particles through the exchange of another particle, consider Figure 11.3.1. Two inline skaters stand stationary and then begin to pass footballs back and forth to each other. As they do this, they will begin to move away from each other. This is due to the conservation of momentum each time they throw and catch the ball. This situation could be likened to two particles experiencing a repulsive (pushing away) force.

A force of attraction can also be illustrated using the same analogy (Figure 11.3.2). If the two skaters now exchange the footballs by trying to grab them out of each other's hands, they will exert a force of attraction on each other. This would cause them to move together and can be likened to two particles experiencing an attractive force.

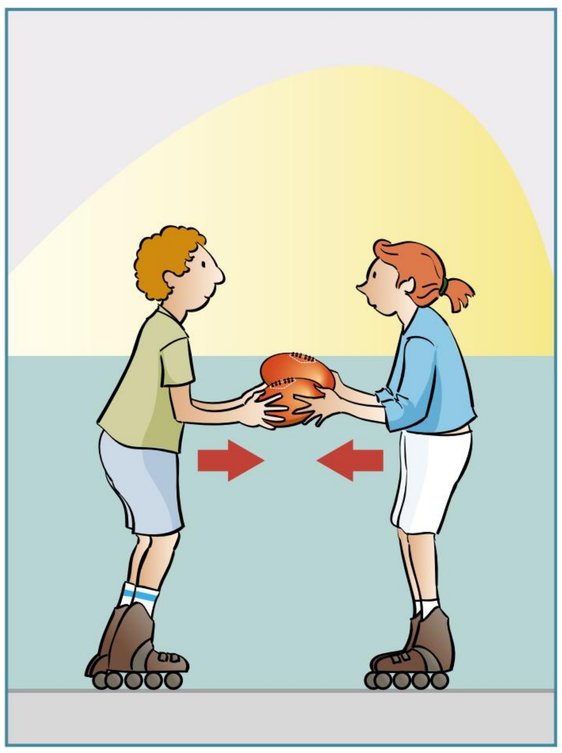


FIGURE 11.3.2 Inline skaters trying to grab footballs act as an analogy for particles experiencing attractive forces due to the exchange of gauge bosons.

Going back to a particle level, Figure 11.3.3 represents an electron approaching another electron. Each electron emits a photon that is absorbed by the other. This causes each electron to experience a force of repulsion due to their electric charges. The photon is responsible for the electromagnetic force acting on the two electrons.

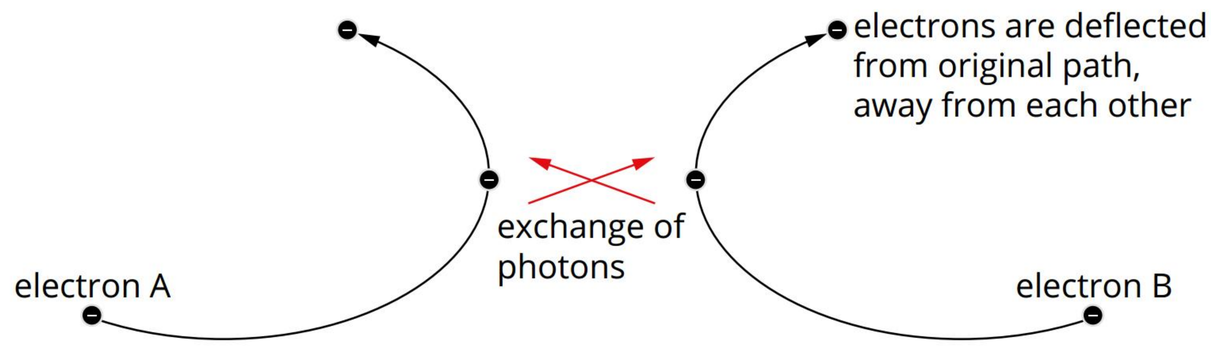


FIGURE 11.3.3 Two electrons approach each other, are repelled and then move away from each other. The two electrons exchange a photon that is the carrier of the electromagnetic force.

Table 11.3.1 gives a summary of the nature of these particles, their strengths and the range over which they can exert a force.

TABLE 11.3.1 Features of the various gauge bosons and the force they are responsible for. (Gravity is included here for completeness, although it is not part of the Standard Model.)

Force	Nature	Relative strength	Range (m)	Force carrier (gauge boson)	Particles affected	Binds matter together to form
strong nuclear	bonds nucleons together, acts between quarks	1	10^{-15} (~size of nucleus)	gluon	quarks, hadrons	hadrons, atomic nuclei
electromagnetic	responsible for both electric and magnetic fields exerting forces of attraction or repulsion	$\frac{1}{137} \approx 0.0073$	infinite	photon	all charged particles	atoms, molecules
weak nuclear	causes radioactive decay	10^{-6}	10^{-18} (less than the width of a proton)	W^+, W^- and Z^0	leptons, quarks, hadrons	–
gravity	a force of attraction between any two objects with mass	6×10^{-39}	infinite	graviton (theoretically predicted but not yet observed)	all particles	planets, stars, galaxies, galaxy groups.

Gravity and the graviton

The Standard Model of particle physics successfully describes the strong nuclear, electromagnetic and weak nuclear forces. Theoretical physics predicts that there should be a gauge boson for gravity too, called a graviton. If this existed, physicists might be able to create a grand unified theory (GUT) that could explain the fundamental behaviour of *all* matter in the universe. However, the graviton has not yet been found.

The behaviour of objects due to the force of gravity is described with spectacular accuracy by the theory of general relativity. This theory basically says that mass tells space how to bend, and bent space tells mass how to move. It applies on the largest scales in the universe and even correctly predicted how binary black holes would emit gravitational waves.

Quantum mechanics mathematically describes the behaviour of subatomic particles. This theory covers the interactions of matter and energy that occur on the smallest scales and is one of the foundations of the Standard Model of particle physics. Einstein's theory of general relativity theoretically does not work for these small scales and high energies. Therefore, the Standard Model of particle physics cannot accommodate gravity and its theoretical exchange particle, the graviton. General relativity and quantum mechanics meet in the physics of black holes. Physicists still do not know exactly what is happening inside a black hole, and until there is an accepted theory that can explain the gravity of particles, black holes remain a mystery.

In the Standard Model, three of the four fundamental forces are exerted via the exchange of particles called gauge bosons. These are:

- strong nuclear force: gluon
- electromagnetic force: photon
- weak nuclear force: W^+, W^- and Z^0 particles.

The following chart (Figure 11.3.4) summarises the classification of particles in the Standard Model of particle physics(as well as the graviton).

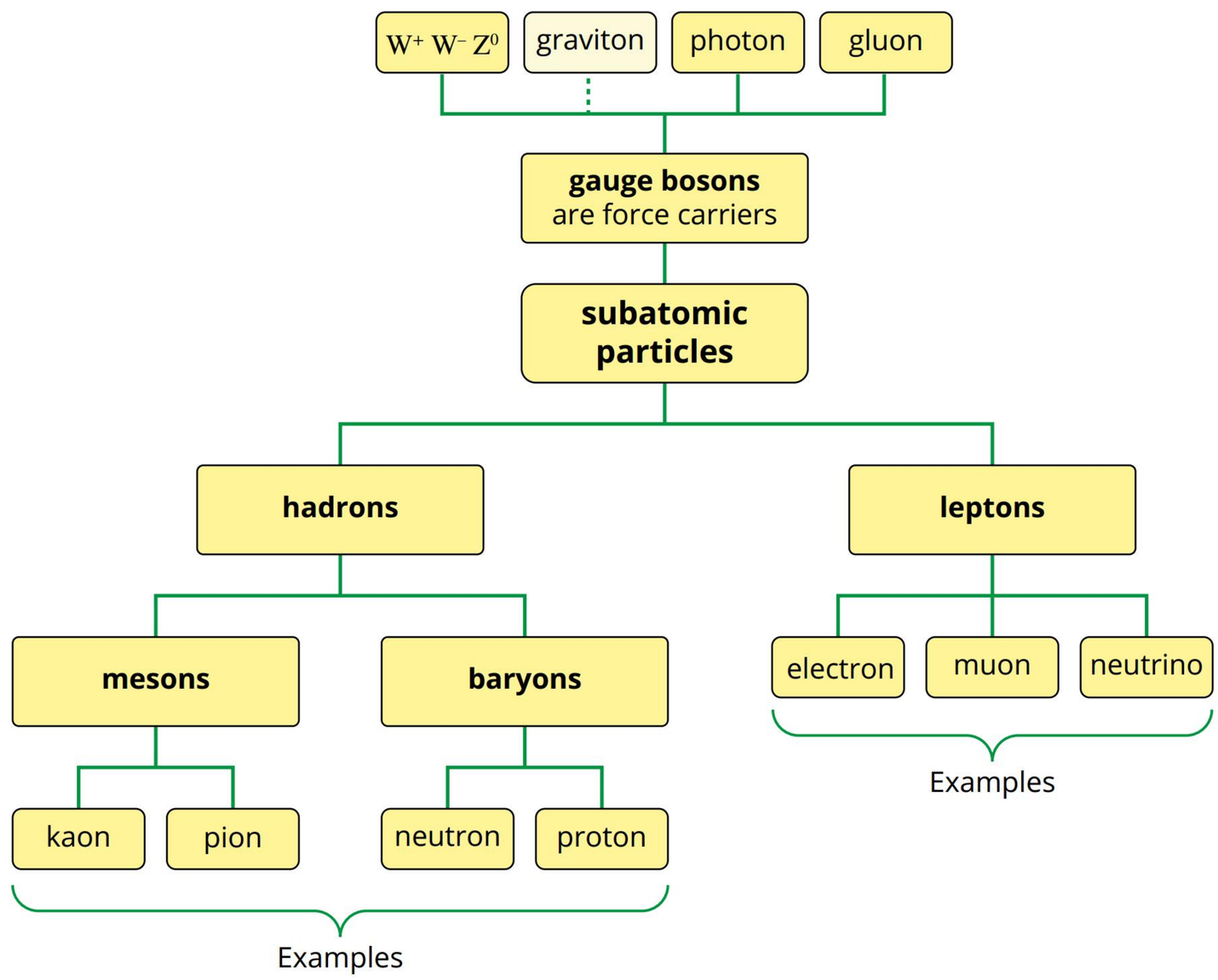


FIGURE 11.3.4 Classification of particles in the Standard Model of particle physics. Remember, the graviton is theoretically predicted but not yet observed.

11.3 Review

SUMMARY

- The four fundamental forces are the strong nuclear force, the electromagnetic force, the weak nuclear force and the gravitational force.
- In the Standard Model, three of these forces are mediated by the exchange of particles called gauge bosons:
  - strong nuclear: gluon
  - electromagnetic: photon
  - weak nuclear: W^+, W^- and Z^0
- Gravity is not a part of the Standard Model; its theoretical gauge boson, the graviton, has not yet been found.

KEY QUESTIONS

Describe

1 Describe what is meant by the term gauge boson.

2 Compare the ranges of the four fundamental forces.

3 A common analogy used to explain how forces are mediated by the exchange of particles involves two skaters passing balls to each other. State what the balls represent in this analogy.

4 State the four fundamental forces and the particles that mediate the particles that have been identified to mediate them.

Apply

5 In what situations is particle physics required rather than relativity, to explain phenomena?

6 Describe how fields are explained by the exchange of gauge bosons.

7 Physicists have not yet managed to successfully integrate gravity into the Standard Model of particle physics. Explain why the omission of gravity is not a disaster for the accuracy of the Standard Model.

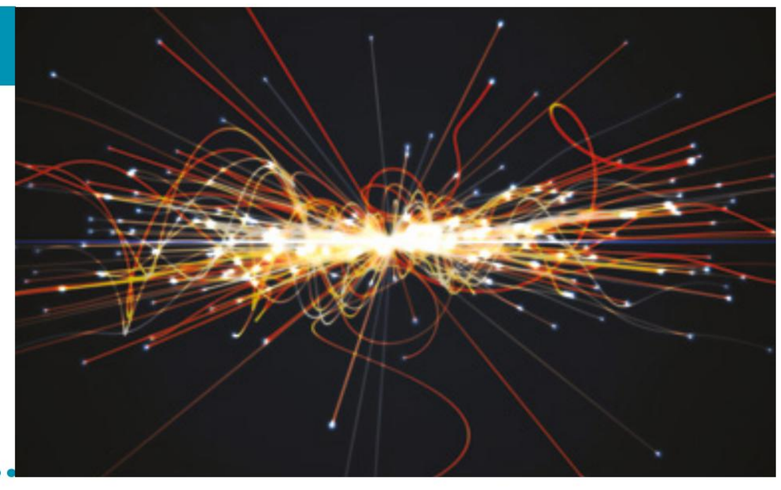
Analyse

8 Some elementary particles are their own antiparticle. For this to be the case, the particle needs to be electrically neutral. Determine which of the gauge bosons (photon, Z^0, W^-) are their own antiparticles.

11.4 Particle interactions

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- understand what happens when matter and antimatter meet
- understand basic particle interactions and how they are represented using particle interaction diagrams
- understand how mass and energy are conserved in particle interactions
- understand the role of symmetry and conservation laws in particle interactions.



Particle physicists strike a serious problem when they study new particle interactions. Even with the laws of conservation of energy, momentum and charge, many products are theoretically possible with the energy available.

Observations show that only a small number of the possible outcomes of an interaction actually occur. Once a large number of events have been observed, it may become clear there are other 'rules' that are important. This means that other properties and conservation laws are needed to summarise the rules, such as the baryon number and lepton number discussed earlier in this chapter.

In this module, you will learn about the conservation laws that govern particle interactions. You will also learn how to show particle interactions graphically in particle interaction diagrams.

CONSERVATION LAWS: MASS–ENERGY

You will recall from *Pearson Physics Queensland Units 1 & 2* that momentum is conserved in all collisions, and that energy too is conserved, even if it is sometimes transformed into other forms such as heat and sound. Energy and momentum are also conserved in particle interactions. In addition, since mass and energy are equivalent, it is necessary to consider:

- the total energy contained in the rest masses of the particles
- the kinetic energy before and after the event.

A simple example is the decay of a stationary neutron to produce a proton, an electron, and an electron antineutrino (Figure 11.4.1).

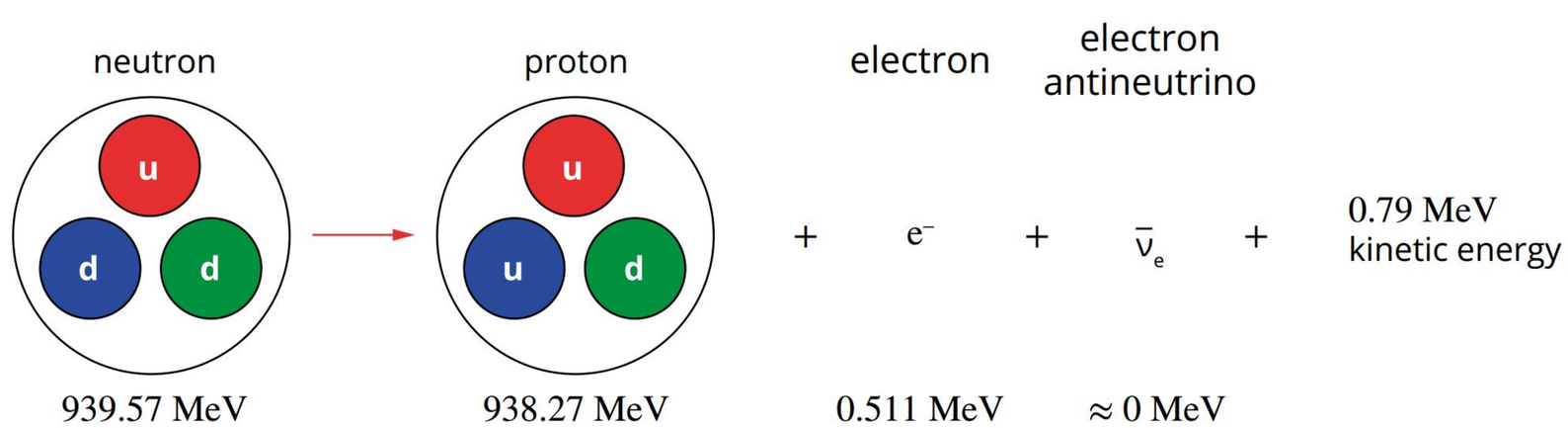


FIGURE 11.4.1 The decay of a stationary neutron is shown to illustrate the conservation of mass–energy. The total energy of the system is conserved.

The mass of the products of the decay of a stationary neutron is less than the mass of the original neutron. Since the neutron is originally stationary, the balance of the energy must be carried away as the kinetic energy of the products. The energy in the mass of the particles is determined using $E = mc^2$, where m is their rest masses. So the mass of a particle is often expressed in units of energy such as MeV, as seen in Figure 11.4.1.

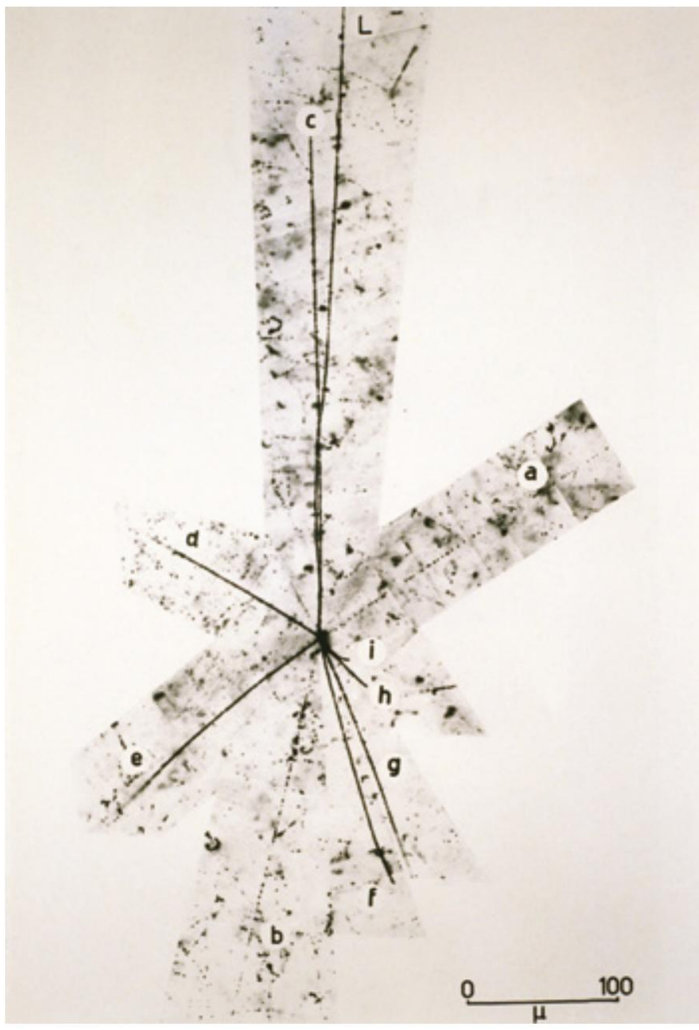


FIGURE 11.4.2 This image records a proton–antiproton annihilation. This event was recorded in 1955 in a photographic emulsion at the Bevatron accelerator at the Lawrence Berkeley Laboratory, California, USA.

This decay will obey the law of conservation of energy, as the energy stored within the mass of the neutron before the decay is equal to the sum of the energies stored within the mass of the products, plus their kinetic energies, after the decay. The momentum carried away by the products would have to be in different directions so that it adds to zero. This would mean that the law of conservation of momentum is obeyed so that the total momentum before (zero) is equal to the total momentum after (zero).

MATTER VERSUS ANTIMATTER: ANNIHILATION

An interesting example of the conservation of energy is seen when matter and antimatter meet. A matter particle and its antimatter particle will destroy, or **annihilate**, each other when they collide, releasing energy according to $\Delta E = \Delta mc^2$. This is observed and exploited on a daily basis in experiments and applications involving antimatter.

Figure 11.4.2 shows an antiproton entering along the track marked L (at top of image), before colliding with a proton. When the proton and antiproton mutually annihilate, the mass of the proton and antiproton is converted to energy.

Another example is the annihilation of an electron and positron. The matter in the electron and positron is converted into energy in the form of two photons. These photons have an energy equivalent to the mass of the electron and positron, according to $\Delta E = \Delta mc^2$.

The opposite of annihilation is also observed. This is called particle–antiparticle **pair production**. Energy in the form of a photon can create a particle–antiparticle pair if the photon has energy greater than or equal to the mass of the particle–antiparticle pair. Pair production also illustrates the relationship between mass and energy in Einstein's equation. The tracks of the new particles form the 'star' pattern that can be seen in Figure 11.4.2.

Matter and antimatter particles are annihilated when they meet, with a release of energy according to $E = mc^2$

Worked example 11.4.1

CONSERVATION OF MASS–ENERGY

A 2.00 MeV gamma ray photon interacts with an atomic nucleus and an electron–positron pair is produced. Each particle created has a mass of 0.511 MeV. Calculate how much kinetic energy is carried away by the particle–antiparticle pair produced.

Thinking	Working
The energy of the gamma ray photon is conserved and is equal to the total mass–energy of the particles produced plus the kinetic energy (E_k) of those particles.	$2.00\,\text{MeV} = 2 \times 0.511\,\text{MeV} + E_k$
Solve for the kinetic energy.	$2.00\,\text{MeV} = 1.022\,\text{MeV} + E_k$
Calculate the answer.	$E_k = 0.978\,\text{MeV}$

➤ Try yourself 11.4.1

CONSERVATION OF MASS–ENERGY

A 1.20 MeV gamma ray photon interacts with an atomic nucleus and an electron–positron pair is produced. Each particle created has a mass of 0.511 MeV. Calculate how much kinetic energy is carried away by the particle–antiparticle pair produced.

CONSERVATION LAWS: CHARGE, LEPTON AND BARYON NUMBERS

In Module 11.2, you learnt about the properties called baryon and lepton numbers. These are just two of a number of properties that describe particles, and must also be conserved in all particle interactions.

Conservation of baryon number is where the baryon number of the particles before the interaction needs to sum to the baryon number of the particles after the interaction. To determine the baryon number before and after the interaction:

> $B = n_b - n_{\bar{b}}$
>
> where
>
> B is the baryon number
>
> n_b is the number of baryons
>
> $n_{\bar{b}}$ is the number of antibaryons.

Notice that only baryons are considered in calculating the baryon number.

Similarly, the lepton number is also conserved, and is summed before and after the interaction. For the lepton number, this sum is compared for each type (or generation) of lepton number as they are conserved separately rather than being combined. For example for the electron lepton numbers, consider electrons, and electron neutrinos for a +1 electron lepton number, and positrons and electron antineutrinos for a −1 electron lepton number.

> $L = n_l - n_{\bar{l}}$
>
> where
>
> L is the lepton number
>
> n_l is the number of leptons
>
> $n_{\bar{l}}$ is the number of antileptons

Conservation of lepton number can be seen when a muon decays into an electron, an electron antineutrino and a muon neutrino:

$$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$$

Lepton numbers in this decay must be conserved. Each type of lepton number must be considered separately.

First, consider the electron lepton number.

- electron lepton number before the interaction:

  $L = n_l - n_{\bar{l}}$
  $= 0 - 0$
  $= 0$
- electron lepton number after the interaction:

  $L = n_l - n_{\bar{l}}$
  $= 1 - 1$
  $= 0$

The electron lepton number is the same before and after the interaction, so it is conserved.

Then, consider the muon lepton number (considering muons, antimuons, muon neutrinos and muon antineutrinos).

- muon lepton number before the interaction:

  $L = n_l - n_{\bar{l}}$
  $= 1 - 0$
  $= 1$
- muon lepton number after the interaction:

  $L = n_l - n_{\bar{l}}$
  $= 1 - 0$
  $= 1$

> Conservation laws can be used to predict the outcome of particle interactions.

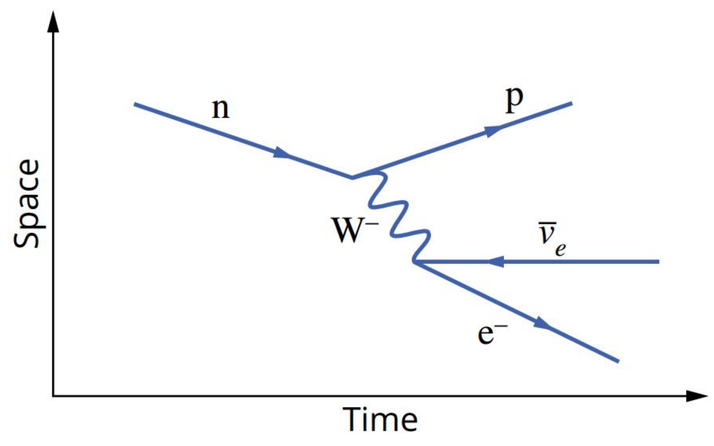


FIGURE 11.4.3 The particle interaction diagram for a neutron decaying into a proton.

The muon lepton number is the same before and after the interaction, so is conserved. You can see that each type of lepton number is the same before and after the decay.

Similarly, electromagnetic charge is conserved before and after the decay: the muon has a charge of $-1e$, as does the electron; the neutrinos do not carry charge.

Figure 11.4.3 shows beta negative decay, which involves a neutron changing into a proton within a nucleus, with the emission of an electron and an electron antineutrino from the nucleus:

$$n \rightarrow p + e^- + \bar{\nu}_e$$

Lepton numbers, baryon numbers and electromagnetic charge must all be conserved in this decay.

Since the only leptons in this decay process are of the electron generation, only the electron lepton number needs to be checked among the lepton numbers. However, the conservation of baryon number and charge must also be considered.

First, consider the electron lepton number.

- electron lepton number before the interaction:

$$\begin{aligned} L &= n_l - n_{\bar{l}} \\ &= 0 - 0 \\ &= 0 \end{aligned}$$

- electron lepton number after the interaction:

$$\begin{aligned} L &= n_l - n_{\bar{l}} \\ &= 1 - 1 \\ &= 0 \end{aligned}$$

The electron lepton number is the same before and after the interaction, so is conserved.

Then, consider the baryon number.

- baryon number before the interaction:

$$\begin{aligned} B &= n_b - n_{\bar{b}} \\ &= 1 - 0 \\ &= 1 \end{aligned}$$

- baryon number after the interaction:

$$\begin{aligned} B &= n_b - n_{\bar{b}} \\ &= 1 - 0 \\ &= 1 \end{aligned}$$

The baryon number is the same before and after the interaction, so is conserved.

For the electromagnetic charge:

- charge on a neutron = 0
- charge on a proton = $+1e$
- charge on an electron = $-1e$
- charge on an electron antineutrino = 0

(+1) = 0 + (+1) + 0, therefore charge is conserved.

You can see that the electromagnetic charge is conserved at all points of this decay. The W^- boson carries a charge of $-1e$, which balances the $+1e$ charge of the proton, so that the products of the decay have a combined charge of zero, which matches the charge on the original neutron. The W^- boson then becomes an electron (charge of $-1e$) and electron antineutrino (charge of zero), so charge is conserved. At the quark level, a down quark (charge $-\frac{1}{3}e$) changes to an up quark (charge $+\frac{2}{3}e$), a difference of $+1e$, which is balanced by the $-1e$ charge on the W^- boson.

Other properties are conserved in interactions, such as strangeness, charm and bottomness. Quantities called spin and parity are also conserved, but these are beyond the scope of this course.

Worked example 11.4.2

CONSERVATION IN PARTICLE INTERACTIONS

Prove that the following interaction is possible using conservation of electromagnetic charge, lepton number and baryon number:

$$p \rightarrow n + e^{+} + \nu_e$$

Thinking	Working
Consider the electromagnetic charge in the interaction.	charge on a proton = +1*e* charge on a neutron = 0 charge on a positron = +1*e* charge on an electron neutrino = 0 (+1) = 0 + (+1) + 0, therefore charge is conserved
Consider the baryon numbers in the interaction.	number of baryons before the interaction: $n_b = 1$ number of antibaryons before the interaction: $n_{\bar{b}} = 0$ baryon number before the interaction: $B = n_b - n_{\bar{b}}$ $= 1 - 0$ $= 1$ number of baryons after the interaction: $n_b = 1$ number of antibaryons after the interaction: $n_{\bar{b}} = 0$ baryon number after the interaction: $B = n_b - n_{\bar{b}}$ $= 1 - 0$ $= 1$ Baryon number is the same before and after the interaction, so is conserved.
Consider the lepton numbers in the interaction. The only leptons involved are a positron (antielectron) and an electron neutrino, both of which belong to the electron generation. Therefore, you only need to focus on the conservation of the electron lepton number, and you do not need to consider the conservation of muon or tau lepton numbers, as no muons or taus are present in this interaction.	For the electron lepton number: number of leptons before the interaction: $n_l = 0$ number of antileptons before the interaction: $n_{\bar{l}} = 0$ electron lepton number before the interaction: $L = n_l - n_{\bar{l}}$ $= 0 - 0$ $= 0$ number of leptons after the interaction: $n_l = 1$ number of antileptons after the interaction: $n_{\bar{l}} = 1$ electron lepton number after the interaction: $L = n_l - n_{\bar{l}}$ $= 1 - 1$ $= 0$ Electron lepton number is the same before and after the interaction, so is conserved.

➤ Try yourself 11.4.2

CONSERVATION IN PARTICLE INTERACTIONS

Prove that the following interaction is not possible, using the conservation of electromagnetic charge, lepton number and baryon number:
$\bar{\nu}_e + n \rightarrow p + e^-$

PARTICLE INTERACTION DIAGRAMS

Particle interactions and decays can be illustrated using a simple diagram called a **particle interaction diagram**.

Particle interaction diagrams are a simple way to illustrate particle decays and interactions.

Interactions between particles that produce some change, or are observed by a particle detector, are commonly known as events. Those interactions that result in the formation of new particles are sometimes referred to as reactions. Interactions can involve attractive or repulsive forces, decay, annihilation, or pair production.

An example of a repulsive interaction involving the electromagnetic force would be the scattering of one electron by another. This example is illustrated using a particle interaction diagram in Figure 11.4.4. It shows two electrons approaching each other (on the vertical axis) over time (the horizontal axis) and exchanging a photon. This causes each electron to be repelled and therefore change direction.

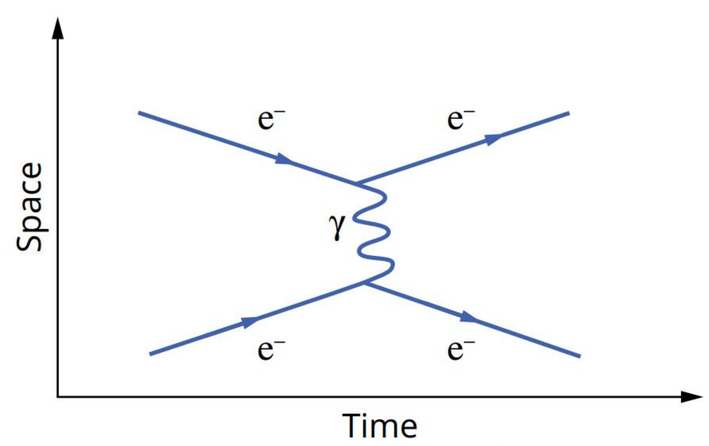


FIGURE 11.4.4 A particle interaction diagram showing the interaction of two electrons (e^-). During this scattering event, a photon (γ) is exchanged.

It is important to note that the directions of the arrows in Figure 11.4.4 do not indicate the direction in which the particles travel, rather it indicates how each particle travels in time; for example, an antiparticle is always shown as moving backwards in time. The simplest information you can gather from these diagrams are the particles involved. There are complex rules that govern these diagrams, as they are a graphical representation of mathematical expressions. You can see by examining Figure 11.4.4 that space is represented on the *y*-axis and time on the *x*-axis. The particles are represented by straight-line arrows with a letter indicating the type of particle shown. The gauge bosons are often represented by wiggly or dashed lines with a letter indicating which gauge boson is involved.

Figure 11.4.5 shows beta negative decay, a decay you may be familiar with from *Pearson Physics Queensland Units 1 & 2* Chapter 3. The equation for this is:

$$n \rightarrow p + e^- + \bar{\nu}_e$$

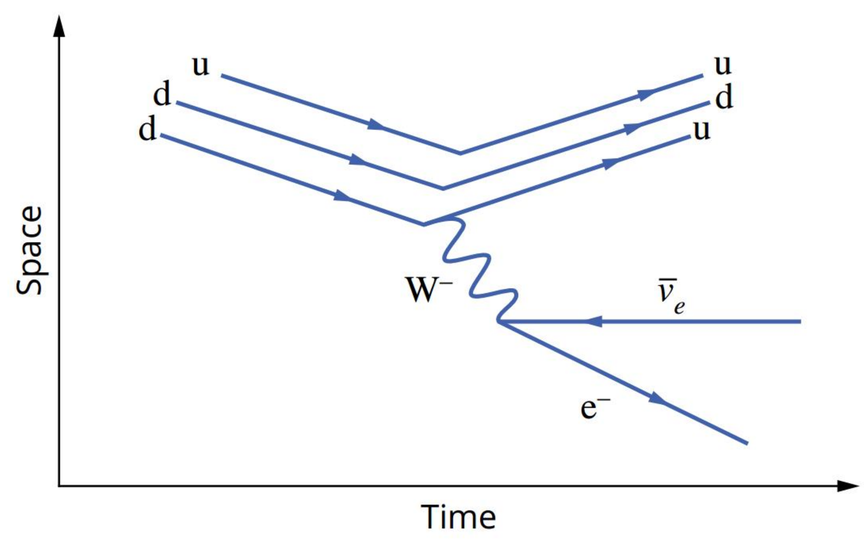


FIGURE 11.4.5 The particle interaction diagram for the same decay, showing what happens at the quark level.

Figure 11.4.5 shows what happens to the neutron's quarks: a down quark changes to an up quark. This is only possible via the weak nuclear force and the emission of a W^- gauge boson.

There are two different interactions between electrons and positrons that are within the scope of this course. Figure 11.4.6 shows the annihilation of an electron and a positron, followed by an electron-positron pair production. The mass of the initial electron and positron is converted into energy in the form of the kinetic energy of a photon, which then produces an electron and positron pair.

The second electron positron interaction is Bhabha scattering shown in Figure 11.4.7. Bhabha scattering is different to annihilation in that at no time does the electron and positron not exist. This can be seen in the particle interaction diagram by following the arrows of the particles and how the particles do not disappear. Instead a photon is exchanged between the electron and the positron, allowing the particles to scatter from each other.

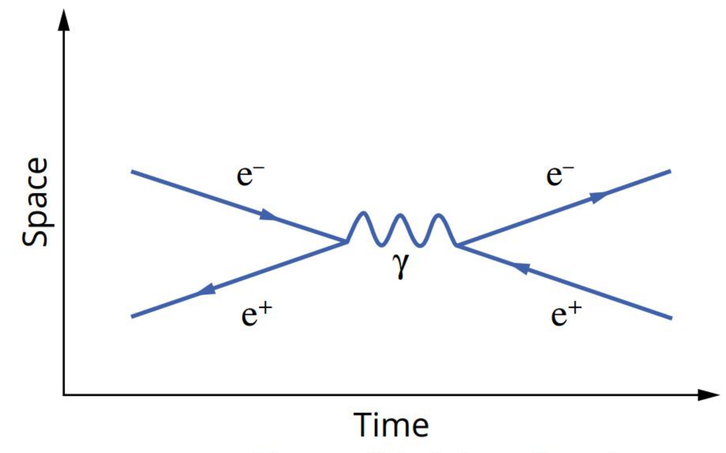


FIGURE 11.4.6 The particle interaction diagram for electron–positron annihilation followed by pair production. Note that during this event the positron appears to be going backwards in time, but this is just a convention for antiparticles in particle interaction diagrams.

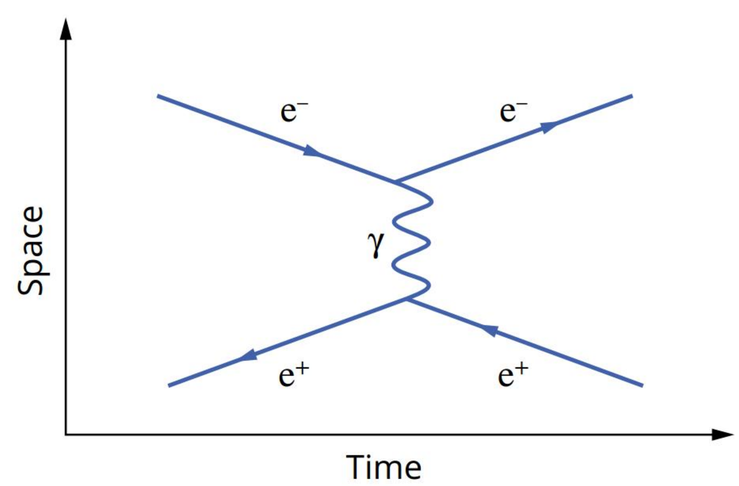


FIGURE 11.4.7 The particle interaction diagram for Bhabha scattering between an electron and positron.

SYMMETRY

Symmetry is important in physics, as it helps to understand and predict how the universe works. When physicists talk about symmetry, they are saying that the laws of physics do not vary under certain transformations. For example, the laws of physics are the same wherever you are in spacetime. The second law of motion, $F = ma$, is the same in your classroom as it is on the other side of the world, or on Mars. This property is called translational symmetry or translational invariance. The same applies for the direction you are facing (rotational symmetry or rotational invariance). Conservation laws are an example of symmetry in physics. These laws apply to particle physics as much as they apply to objects on your scale. There are also several other symmetries in particle physics. It might seem like a very simple, and almost insignificant, point, but symmetry in particle physics allows physicists to predict the behaviour of particles, and their conservation laws enable physicists to determine which particle interactions can happen, and which cannot.

An example of symmetry in particle interactions is electron positron annihilation and pair production. This is symmetry in the time domain as one interaction is the time reverse of the other, so pair production is the reverse of annihilation. These processes are both clear examples of the conservation, in particular, of mass–energy.

Particles also have an internal symmetry, which can help predict the existence of other particles. For example, the baryon number introduced in Module 11.2 is a type of internal symmetry. If a particle exists with a baryon number of +1 (e.g. a proton), symmetry suggests that there must be a corresponding antiparticle with a baryon number of −1 (an antiproton in this case).

Physicists have searched for a theory that can unite the different forces in nature, and have found similarities between the weak nuclear force and the electromagnetic force, which led to the idea that these could be a single electroweak force. However, the force carriers involved are different; W and Z bosons have a relatively high mass, but photons have no mass. Symmetry suggests that the W and Z bosons should have no mass, so the Higgs boson was predicted to explain this, as described in Science as a Human Endeavour 8.

Supersymmetry is an extension of the Standard Model that attempts to explain phenomena not currently explained. Supersymmetry predicts a partner for each particle in the Standard Model that will explain differences in mass between particles. It also could link fermions (a group of elementary particles) and bosons by predicting that there will be a corresponding boson for every fermion, and vice versa. This could provide a way to unify the strong nuclear, electromagnetic and weak nuclear forces at very high energies, such as the conditions at the very start of the universe.

11.4 Review

SUMMARY

- When a matter particle and its antimatter particle collide, they are completely annihilated and produce photons with the equivalent energy of the two particles, calculated by Einstein's mass–energy equation $\Delta E = \Delta mc^2$.
- Lepton number can be determined using:
$$L = n_l - n_{\bar{l}}$$
where n_l is the number of leptons and $n_{\bar{l}}$ is the number of antileptons.
- Baryon number can be determined using:
$$B = n_b - n_{\bar{b}}$$
where n_b is the number of baryons and $n_{\bar{b}}$ is the number of antibaryons.
- In all particle interactions, quantities such as mass–energy, electromagnetic charge, lepton number and baryon number are conserved. These conservation laws put limits on the possible outcomes of any interaction or decay.
- Particle interactions can be illustrated using particle interaction diagrams.
- Symmetry is an important feature of particle physics, helping physicists to predict what particle interactions are possible, and to predict the existence of new particles by considering the conservation laws.

KEY QUESTIONS

Describe

1 In a particle interaction, the mass of the particles after the interaction is less than the mass of the particles before the interaction. State whether energy is conserved in this interaction, and if so describe where the difference in mass has gone.

2 Identify which gauge boson mediates beta negative decay.

3 Describe the similarities and differences between matter particles and their corresponding anti-matter particles

4 Describe the process of electron-electron scattering. Use the particle interaction diagram in Figure 11.4.4 to assist.

Apply

5 Predict the baryon number of the missing particle, X, in the following interaction.

$p^+ + e^- + + \bar{\nu}_e \rightarrow X$

6 Apply conservation laws of electromagnetic charge, lepton and baryon number, to determine if the following interactions are possible:

a $\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$

b $\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$

c $p + n \rightarrow 2p + e^- + \bar{\nu}_e$.

7 Draw and label a particle interaction diagram for each of the following interactions:

a electron–electron repulsion

b beta negative emission.

8 A proton and antiproton, each with a mass of 938 MeV and an additional kinetic energy of 15 MeV between them, annihilate to produce two photons. What is the energy of the photons produced?

Analyse

9 The rest mass energy of an electron or a positron is 0.511 MeV. Determine the minimum energy of the incident photon if a gamma ray photon interacts with an atomic nucleus and an electron–positron pair is produced.

10 A pion+ meson (π^+) decay produces an antimuon and what other particle?

11 A positively charged K meson (K^+) decays into a neutral pion meson (π^0), an electron neutrino (ν_e) and a third particle. Identify the third particle, X, using conservation laws.

$K^+ \rightarrow \pi^0 + \nu_e + X$

Chapter review

11

KEY TERMS

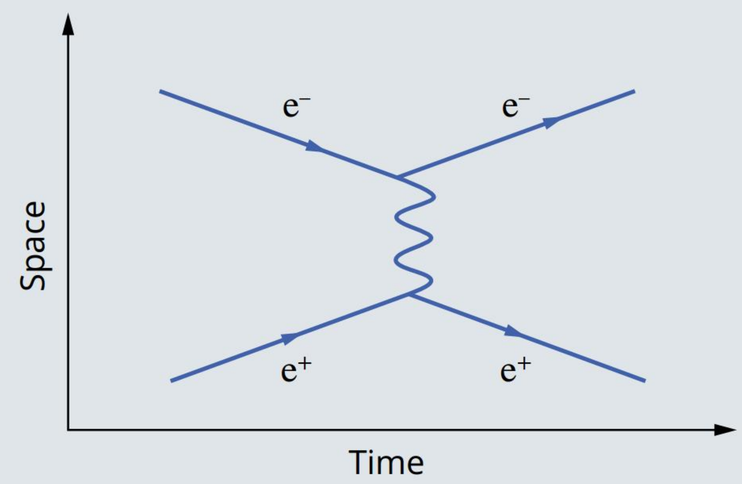
annihilation
antiparticle
baryon
baryon number
colour charge
elementary particle
fermion
gauge boson
gluon
hadron
lepton
lepton number
meson
neutrino
pair production
particle interaction diagram
photon
quantum number
quark
Standard Model
strong nuclear force
W^+, W^- and Z^0
weak nuclear force

KEY QUESTIONS

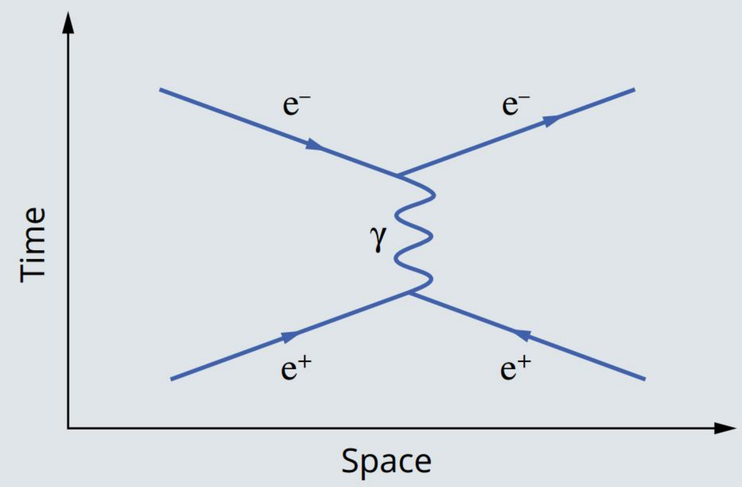
Describe

1 Identify which particle interaction diagram correctly shows Bhabha scattering between an electron and a positron.

A



B



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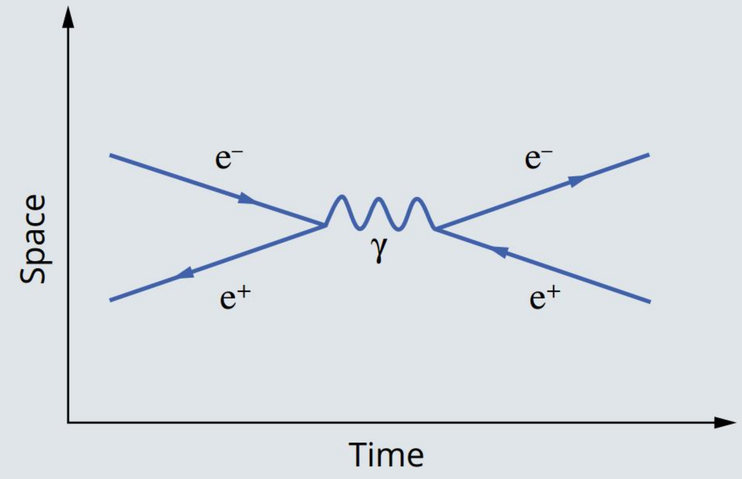

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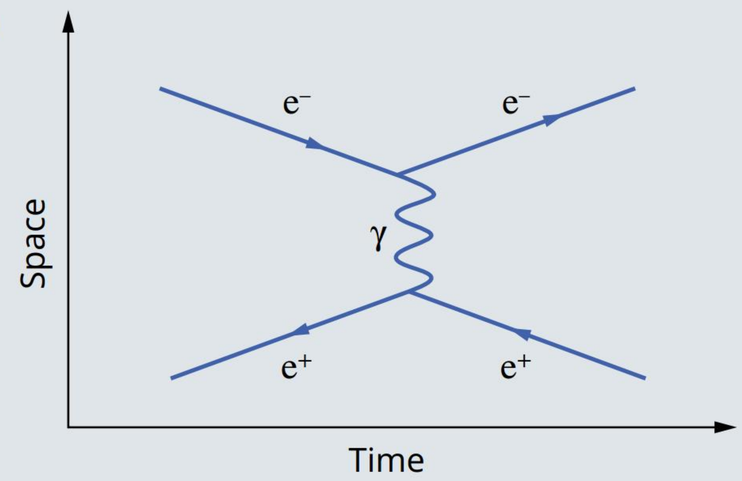


2 Which of the following correctly indicates an antimuon?

A μ^+
B μ^-
C $\bar{\mu}$
D ν_μ

3 Identify which of the following particles has a baryon number of 1.

A τ^-
B s
C n
D $\bar{b}$

4 Identify which of the following gauge bosons has not been experimentally observed.

A gluon
B graviton
C W^+
D Z^0

5 a Identify the fundamental particles that make up fermions.
   b State which quarks make up protons and neutrons.
   c Describe how the Standard Model explains three of the four fundamental forces. As part of your answer, identify the three forces and their associated particle(s). State which force is not explained by the Standard Model.
   d State whether an electron is a composite or a fundamental particle and whether it is a lepton or a hadron.

6 Describe the significance of symmetry in particle interactions considering conservation.

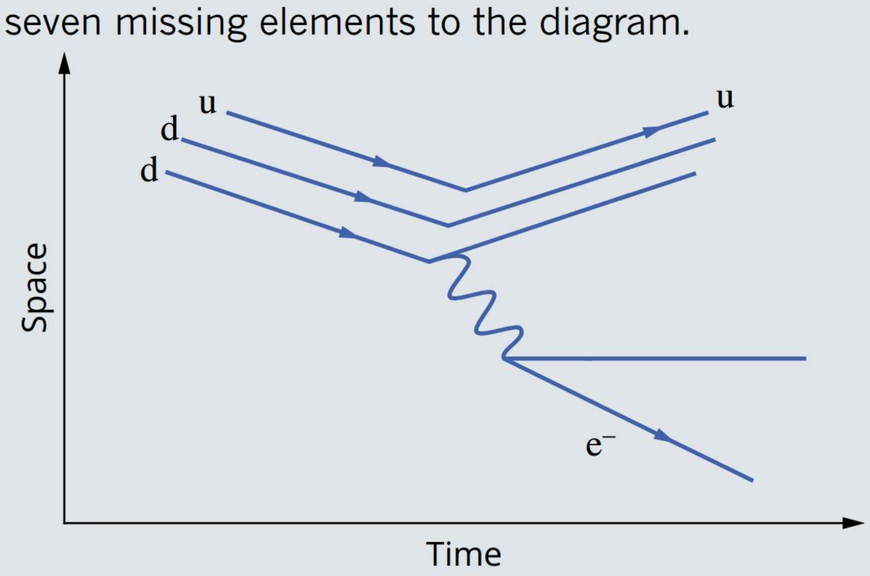
Apply

7 Determine the tau lepton number of the following group of particles.
$e^+ + \tau^+ + \nu_\mu + \nu_\tau$
   A −1
   B 0
   C 1
   D 2

8 In the following interaction, which conservation law is violated?
$p^+ + e^- + \bar{\nu}_e + p^-$
   A lepton number
   B mass–energy
   C electromagnetic charge
   D baryon number

9 Explain all the forces that tau particles experience.

10 Copy the following particle interaction diagram for beta negative decay and fill in the missing parts. There are seven missing elements to the diagram.



11 Draw a concept map to show the division of particles of the Standard Model.

12 Describe what happens in the process called pair production.

13 Archie is revising for a Year 12 physics exam and is confused over the term annihilation. Describe what this term means to help him revise.

14 A neutron in an evacuated container decays to produce a proton and two other particles. The proton is then attracted to an electron and becomes a hydrogen atom. The atom then slowly drifts to the base of the container.
List the four fundamental forces that have been involved in the sequence of events described above from first to last.

15 Explain how the proton gains a +1 charge from its constituent quarks and how a neutron gains a neutral charge from its constituent quarks.

Analyse

16 Compare and contrast the properties of quarks and leptons.

17 Compare the four gauge bosons, considering range, charge and strength of interaction.

18 Pair production in particle physics usually refers to the production of an electron–positron pair from a photon. However, under certain circumstances the pair production of a muon–antimuon pair or a proton–antiproton pair is possible.
In one interaction, an electron and positron annihilate to produce a photon, from which a muon–antimuon pair is produced. Calculate the minimum energy of the photon that produced the muon–antimuon pair if the rest mass energy of a muon is 105.7 MeV.

19 Determine whether the following interaction is possible by considering the conservation of electromagnetic charge, lepton number and baryon number.
$$\bar{\nu}_e + p \rightarrow n + e^+$$

Interpret

20 An annihilation between an electron and a positron is observed to create two photons. Explain why two photos were observed instead of one.
$$e^- + e^+ \rightarrow 2_\gamma$$

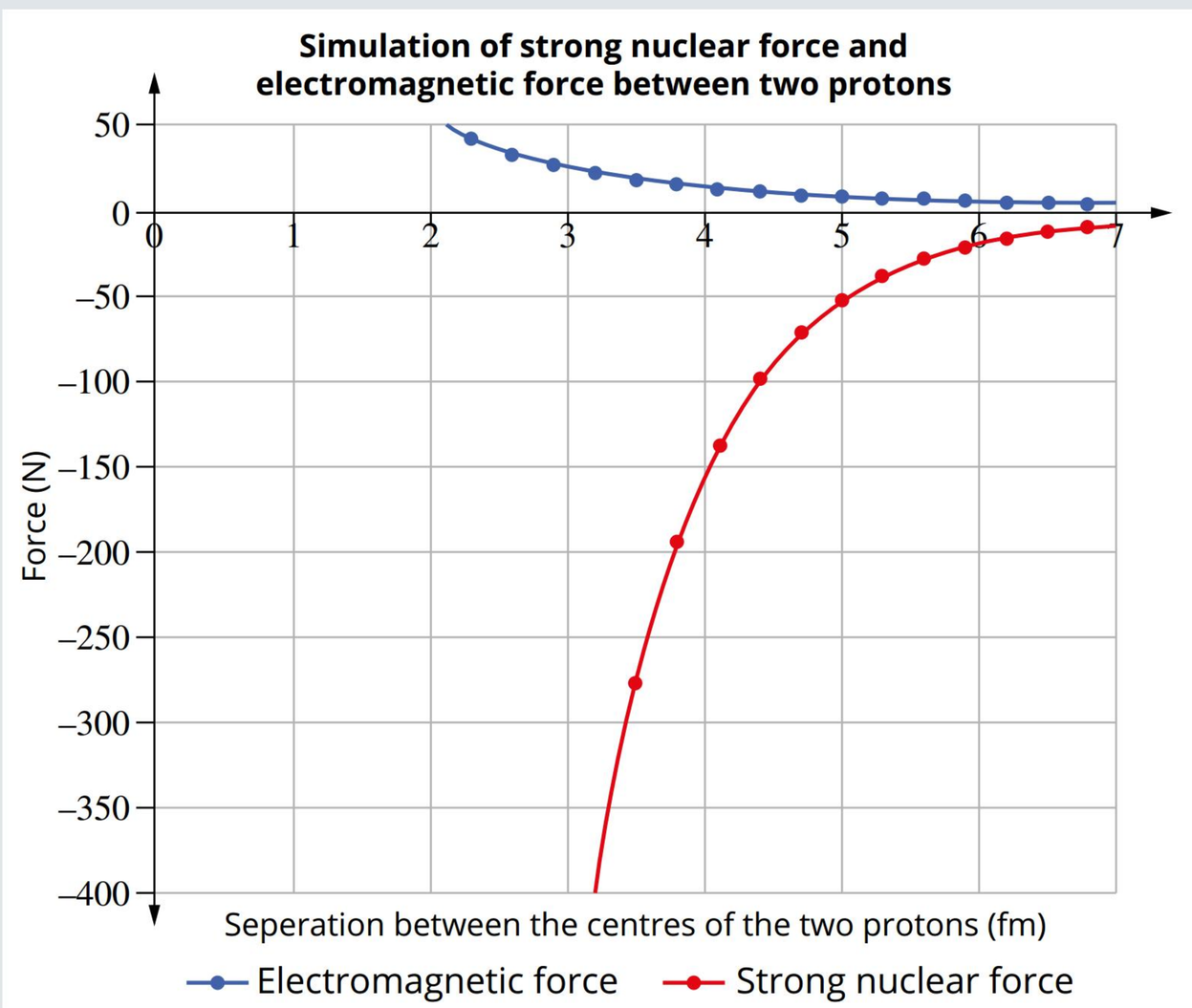
Data analysis

DATA SET 1

The information below applies to Questions **1**–**4**.

Data was modelled to compare the strong nuclear force between two protons and the electromagnetic force between two protons. Three different simulations (Sim) were used for electromagnetic force and for the strong nuclear force. Note the strong nuclear force is attractive at these distances so is shown as negative.

Separation (fm)	Electromagnetic force				Strong nuclear force			
	Sim 1	Sim 2	Sim 3	Average	Sim 1	Sim 2	Sim 3	Average
2.3	44.0	43.7	43.6	43.8	−1418.2	−1602.4	−1172.5	−1397.7
2.6	34.5	34.2	34.1	34.2	−911.2	−1042.2	−747.0	−900.2
2.9	27.7	27.5	27.4		−601.4	−696.3	−488.9	−595.5
3.2	22.8	22.6	22.5	22.6	−405.6	−475.3	−326.9	−402.6
3.5	19.0	18.9	18.8	18.9	−278.4	−330.2	−222.5	−277.0
3.8	16.1	16.0	16.0	16.0	−193.9	−232.8	−153.7	−193.5
4.1	13.9	13.7	13.7	13.8	−136.8	−166.2	−107.5	−136.8
4.4	12.0	11.9	11.9	12.0	−97.5	−120.0	−76.0	−97.8
4.7	10.5	10.5	10.4	10.5	−70.2	−87.4	−54.2	−70.6
5.0	9.3	9.2	9.2	9.3	−50.9	−64.2	−39.0	−51.4
5.3	8.3	8.2	8.2	8.2	−37.2	−47.5	−28.3	−37.6
5.6	7.4	7.4	7.3	7.4	−27.4	−35.3	−20.6	−27.8
5.9	6.7	6.6	6.6	6.6	−20.2	−26.5	−15.1	−20.6
6.2	6.1	6.0	6.0	6.0	−15.1	−19.9	−11.1	−15.4
6.5	5.5	5.5	5.5	5.5	−11.2	−15.1	−8.3	−11.5
6.8	5.0	5.0	5.0	5.0	−8.4	−11.4	−6.1	−8.7



Question 1 (1 mark)
Use the graph to identify the force due to the strong nuclear force at a separation of 4.5 fm.

Question 2 (1 mark)
Determine the average electromagnetic force for a separation of 2.9 fm.

Question 3 (2 marks)
Calculate the percentage uncertainty in the strong nuclear force at 3.5 fm.

Question 4 (3 marks)
Contrast the relationship between separation, and the electromagnetic force and the strong nuclear force.

REVIEW QUESTIONS

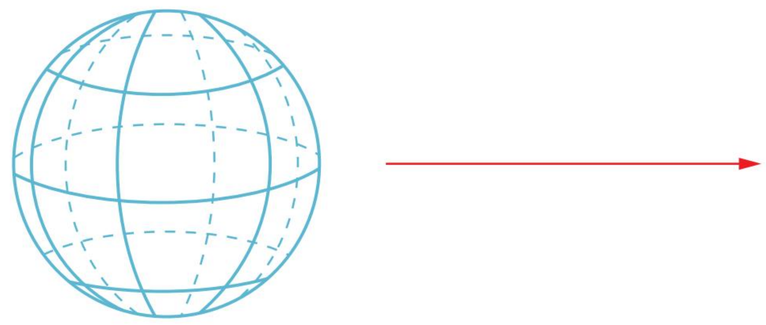
Topic 1: Special relativity

Multiple choice

1 Select the option that best describes inertial frames of reference.

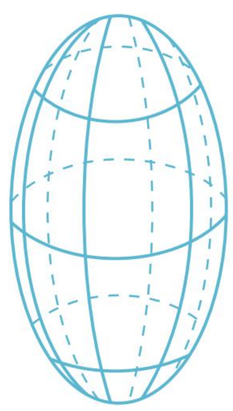
A Inertial frames move at a constant velocity.
B Inertial frames accelerate at a constant rate.
C Inertial frames change velocity at a constant rate.
D Inertial frames do not move relative to one another.

2 A sphere is approaching an observer at a speed of 0.8*c*.

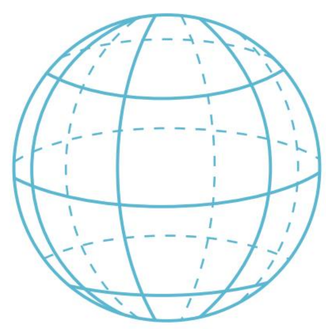


Identify which sphere would be measured by the observer.

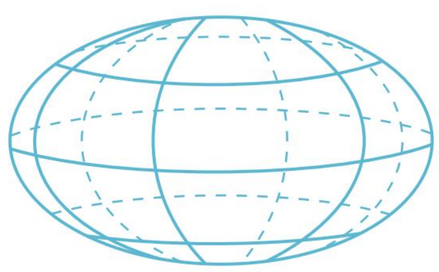
A



B



C



D

3 Identify the two postulates of special relativity from the following options.

A The speed of light in a vacuum is constant in all inertial frames of reference and the laws of physics only apply at classical speeds.
B The laws of physics are the same in all frames of reference and the speed of light is constant in all frames of reference.
C The laws of physics are the same in all inertial frames of reference and all speeds are relative to the observer's frame of reference.
D The laws of physics are the same in all inertial frames of reference and the speed of light in a vacuum is constant in all inertial frames of reference.

4 Select the statement that explains why no object with mass can accelerate to travel at the speed of light.

A It would require infinite energy.
B The object would experience infinite time.
C The object would have a relativistic momentum of zero, and disappear.
D The mass of the object would become too small for a force to accelerate it.

5 Assume you are approaching a light beacon while travelling at half the speed of light (0.5*c*). What would you measure the speed of light from the beacon to be?

A 1.0*c*
B 1.5*c*
C 0.50*c*
D 0.75*c*

6 Select the most accurate description of simultaneity from the following options.

A It is the ability to measure the time between two events.
B Two events can never be exactly simultaneous due to different frames of reference.
C Events occurring at the same time will be simultaneous in all reference frames as a consequence of the constant speed of light.
D Two events that occur at the same time in one reference frame may occur at different times in a different reference frame.

7 Select the most accurate description of rest mass from the following options.

A It is the mass that has been converted to energy.
B It is the mass of an object measured in the same reference frame as the observer.
C It is the mass of an object measured in an inertial reference frame.
D It is the mass of an object measured when the absolute velocity is zero.

8 Identify which of the following statements concerning Einstein's equation $\Delta E = mc^2$ is correct.

A Mass is greater than energy.
B Energy and mass are equivalent.
C Mass and the speed of light are equivalent.
D Energy and the speed of light are equivalent.

9 An electron with a rest mass of 9.109×10^{-31} kg travels past an observer at a speed of $2.0 \times 10^{8}\,\mathrm{m\,s^{-1}}$. Identify the relativistic momentum of the electron.

A $2.4 \times 10^{-22}\,\mathrm{kg\,m\,s^{-1}}$
B $1.8 \times 10^{-22}\,\mathrm{kg\,m\,s^{-1}}$
C $1.4 \times 10^{-22}\,\mathrm{kg\,m\,s^{-1}}$
D $3.2 \times 10^{-22}\,\mathrm{kg\,m\,s^{-1}}$

10 Amy and Jorge synchronise their watches on Earth. Amy remains on Earth while Jorge takes a round trip to Pluto at near light speed. Determine whose watch will show the greater passage of time when they reunite.

A impossible to tell
B Amy's watch (on Earth)
C Jorge's watch (on the spaceship)
D Amy and Jorge's watches are still synchronised

Short answer

1 **a** Galilean relativity states there is no absolute velocity, rather, all velocities are relative. Explain what this means, using an example. Use numerical values in your example.

b Explain how special relativity differs from Galilean relativity with respect to the speed of light.

2 The time t_0 and the length L_0 are referred to as the proper time and proper length. Explain what is meant by proper time and proper length, and illustrate with an example to compare them to relativistic time and relativistic length.

3 Einstein's theory of special relativity is based on the principles that:

- the speed of light in a vacuum is an absolute constant and
- the laws of physics are the same in all inertial frames of reference.

Identify the apparent contradiction of accepting these two principles, and explain how Einstein's theory of special relativity resolves this apparent contradiction.

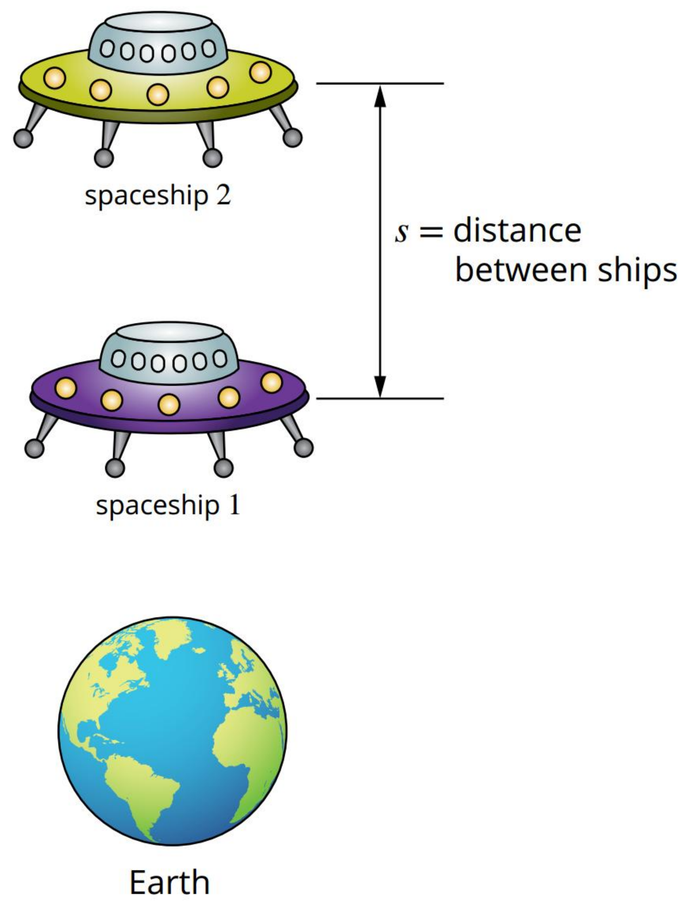
4 The mass of reactants is measured prior to undergoing a reaction in a nuclear reactor. The mass is measured again after the reaction has taken place. A mass defect of 800 g is noted. Calculate the amount of energy that has been released in this reaction.

5 **a** A comet is travelling away from Earth at a speed of 0.180*c*. A space probe that has been sent to observe the comet measures the real length of its long axis to be 3.20 km. Calculate the length the comet appears to be from Earth when the long axis is travelling away from Earth.

b The comet is rotating on its axis such that the long axis is at times perpendicular to the observer on Earth. Calculate the length the comet will appear to have for an Earth observer when it is in this position.

6 The proper length of a spacecraft is 75 m. As it passes by a space station, its length is measured to be 60 m. Calculate the speed of the spacecraft relative to an observer on the space station.

7 Two spaceships are travelling side by side at the same high velocity towards the right. As they pass Earth, the captain of spaceship 1 sends a radio signal (hence it is travelling at *c*) to the captain of spaceship 2. The captain of spaceship 2 then sends a return signal. This situation is illustrated below.



The captains of the two spaceships record the time for the signals to pass between them as less than that recorded by an observer at the space command centre on Earth. Explain this apparent contradiction with the aid of a labelled diagram.

8 A space probe is sent to make observations of a planet orbiting a nearby star. The planet is 24.6 light-years from Earth and the probe is sent from Earth with a speed 0.820*c*. The probe carries an atomic clock that was synchronised with a similar clock on Earth at the start of the journey.

a Contrast the duration of the journey as measured by the clock on Earth with the duration of the journey as measured by the clock on the probe. Use calculations to support your answer.

b Calculate the distance travelled to reach the planet, as determined from the space probe's frame of reference.

c On arrival at the planet, the space probe sends its measurements back to Earth via radio signal. Compare the signal velocity in Earth's frame of reference with the signal velocity in the probe's frame of reference. Justify your response with reference to relevant physics.

9 One of the pieces of evidence to support Einstein's special theory of relativity is the observation of the lifetimes of muons, which travel at speeds close to the speed of light.

a Contrast the lifetime of a muon travelling at 0.90*c* with the lifetime of a muon as measured by an observer able to travel with the muon. Use calculations to support your answer. Note that the half-life of a muon is 2.2×10^{-6} s.

b As the muon travels through the atmosphere, the observer travelling with the muon measures the height of a hill to be 200.0 m. Calculate the height of this hill as measured on Earth.

c Given the distance that muons need to travel and their short lifetimes, Newtonian physics predicts that muons, created high in Earth's atmosphere, should not be able to reach Earth's surface. This is not what is observed by scientists. Explain how it is possible for muons to strike Earth's surface, given their short lifetimes and long distance to travel.

10 A rocket travels past the International Space Station (ISS) at a speed of 0.98*c* from left to right. The proper length of the ISS is 109 m. When the rocket passes the middle of the ISS, astronauts start stopwatches on both the rocket and the ISS.

a Calculate the length of the ISS according to an astronaut on the rocket.

b Two lamps are placed at either end of the ISS. An astronaut at the midpoint of the ISS observes the lamps to flash simultaneously at time = 0 s. Deduce which lamp flashed first, as determined by the astronaut on the rocket.

c The rocket turns on its engine and begins to decelerate at a constant rate. It comes to a stop and then begins to accelerate back towards the ISS at the same rate. Once the rocket reaches a velocity of 0.98*c*, it continues at a constant velocity towards the ISS.

Determine which stopwatch measures the longest amount of time.

11 Explain why thought experiments such as a train moving at speeds close to the speed of light are a useful tool to communicate scientific ideas.

12 Demonstrate the meaning of the term 'simultaneity' in the form of an analogy.

13 Discuss what implications special relativity has for real-time communication in space travel by considering communication at the speed of light between Earth and a spaceship travelling at close to the speed of light.

14 The Large Hadron Collider is capable of colliding ions of lead at over 99% of the speed of light.

a Calculate the relativistic momentum of a lead ion ($m_0 = 3.4 \times 10^{-25}$ kg) at 0.99*c*.

b Explain the implication relativistic momentum has for the energies recorded in particle accelerator collisions, including why lead is used in these experiments.

Topic 2: Quantum theory

Multiple choice

1 Select the statement that is true of Rutherford's model of the atom.

A The model explains atomic emission spectra.
B The atom carries a net negative charge.
C The atom has a cloud of protons and electrons.
D The atom has a positively charged nucleus surrounded by orbiting electrons.

2 Identify which of the following statements about Bohr's model of the atom is incorrect.

A It adopted quantum mechanical principles.
B It assumed that the inner electron orbits have the most energy.
C It could explain emission spectra for simple atoms like hydrogen.
D It had electrons orbiting a positive nucleus in a set of discrete orbits.

3 The surface temperature of Earth is 15.0°C. The peak wavelength of Earth's black-body radiation is:

A 107 μm
B 10.7 mm
C 10.1 μm
D 101 μm

4 Select the correct description of a photon from the following options.

A A photon has no momentum.
B A photon has a rest mass of zero.
C Photons travel at a speed proportional to their frequency.
D A photon has a mass approximately equal to the mass of an electron.

5 Identify from the following options the energy of a photon with a wavelength of 6.45×10^{-7} m.

A 3.08×10^{-33} J
B 3.08×10^{-19} J
C 4.27×10^{-40} J
D 4.27×10^{-6} J

6 Identify which of the following statements about the photoelectric effect is correct.

A The photoelectric effect is used as evidence to support the model of light as a transverse electromagnetic wave.

B The minimum energy of a photon needed to eject an electron from a metal surface varies with the frequency of the incident light.

C The kinetic energy of electrons ejected from a metal surface will increase as the intensity of light incident on the surface is increased.

D For light above the required minimum frequency, an increase in the intensity of the incident photons on a metal surface will increase the number of electrons ejected from its surface.

7 Select the maximum wavelength of light that a hydrogen atom will emit when an electron goes from the $n = 2$ energy level to the $n = 1$ energy level. The Rydberg constant for hydrogen is $1.097 \times 10^7\,\text{m}^{-1}$.

A 0.274 nm

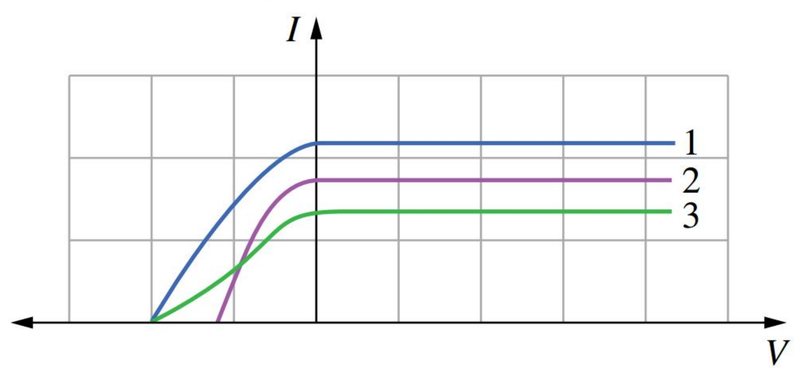
B 121.5 nm

C 0.0082 nm

D 0.0022 nm

8 The following graph was collected during a photoelectric effect experiment. The graph shows the photocurrent measured as a function of potential difference applied.

Photocurrent measured as a function of potential difference applied



Select the correct statement.

A Light 2 has less intensity than light 3.

B Light 2 is a higher frequency than light 1.

C Light 1 and light 3 are the same intensity but have different frequencies.

D Light 1 and light 3 are the same frequency light but have different intensities.

9 Identify from the following, evidence that supports the particle theory of light.

A photoelectric effect, polarisation of light

B black-body radiation, photoelectric effect

C the double-slit experiment, polarisation of light

D the double-slit experiment, photoelectric effect

10 In the constellation Orion, the star Rigel is blue-white in colour, while the star Betelgeuse is reddish. Select the best explanation of these observations from the options below.

A Rigel is closer than Betelguese.

B Rigel is cooler than Betelguese.

C Rigel is hotter than Betelguese.

D Rigel is further way than Betelguese.

Short answer

1 Decide whether an atom will emit photons (light) of any energy when an electron falls from a higher energy level to a lower energy level. Explain your answer.

2 State two pieces of evidence that support the wave model of light. For one of these pieces of evidence, describe how it provides evidence for the wave nature of light. Diagrams may be used to assist your explanation.

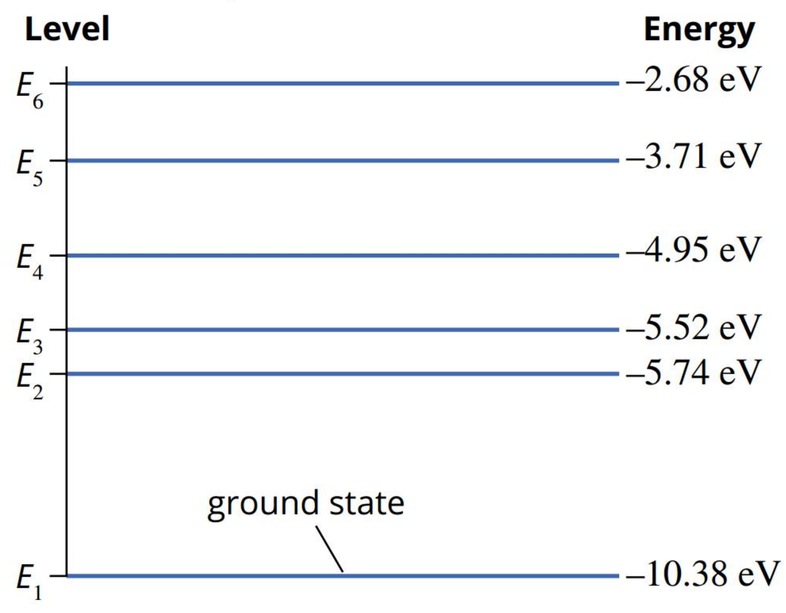
3 Blue light and red light are both shone on a metal surface. Electrons were measured being emitted when the blue light was shone on the metal, but not when the red light was shone.

Describe the concepts 'threshold frequency' and 'work function' using this example.

4 Violet light of wavelength 390 nm is used in a photoelectric effect experiment. When violet light shines on a metal cathode, the stopping voltage measures 0.90 V. Calculate the velocity of the most energetic electrons that are emitted from the metal's surface.

5 Black-body radiation was originally described using a classical model. The peak wavelength was observed to decrease as the temperature increased. Paraphrase the two assumptions Planck made to describe the shape of the curve.

6 The diagram below shows some of the electron energy levels for a mercury atom.



a The line emission spectrum for mercury has a prominent blue line at about 437 nm. Determine between which two energy levels an excited electron will transition between to emit light of this wavelength.

b Identify how many different lines could appear in an emission spectrum for mercury for an electron falling from energy level 4 to the ground state.

7 Explain how Bohr's model of the atom resolved the limitations of the Rutherford model.

8 The double-slit experiment is a key experiment in modern physics.

a Identify whether the double-slit experiment provides evidence for wave or particle characteristics of light.

b Explain how the double-slit experiment demonstrates this evidence.

9 In an experiment to determine the threshold frequency and work function for a particular metal, a researcher measured the kinetic energy of the electrons ejected from the metal's surface at a range of frequencies. The results are tabulated below.

Frequency ($\times 10^{15}$ Hz)	Kinetic energy of electron ($\times 10^{-19}$ J)
2.50	9.055
5.00	25.63
7.50	42.20
10.0	58.78
12.5	75.36

a Create a graph of kinetic energy against frequency.

b Determine the threshold frequency for the metal from the graph.

c Determine the work function for the metal from the graph.

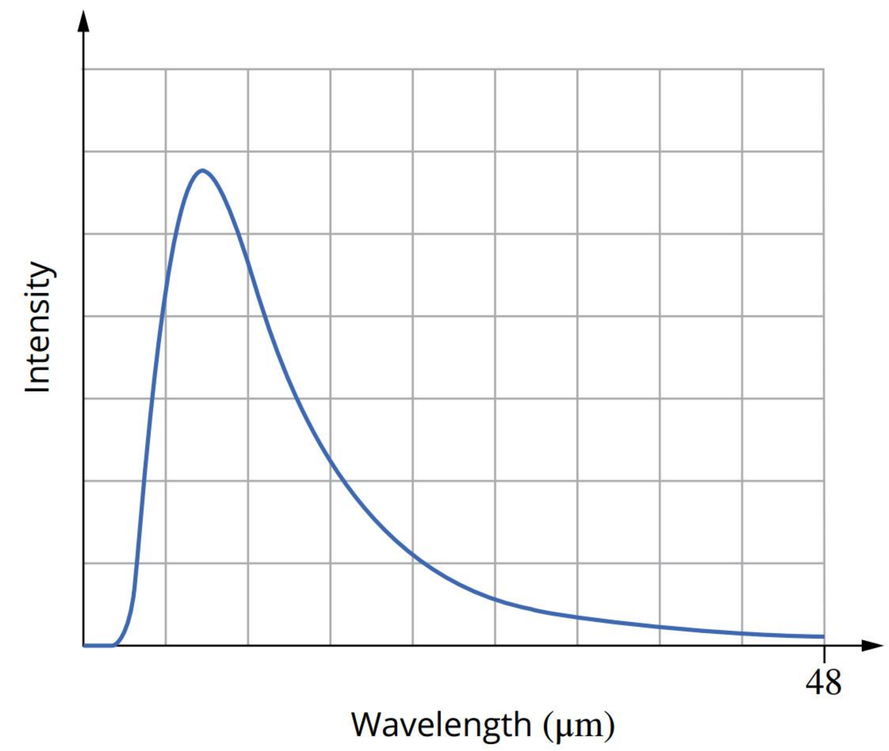
d Determine the value of the gradient, including the significance of this value.

e The researcher carries out the same experiment to determine the threshold frequency and work function for a second metal and graphs the kinetic energy against frequency. Predict the slope of the line for this second metal.

f Explain what evidence the effect studied in this experiment provides about the nature of electromagnetic radiation.

10 A heater is measured to emit radiation with a peak wavelength of 8.21 μm, as shown in the spectrum below.

Intensity versus wavelength for a heater



a Describe the nature of the waves being emitted from the radiator, including in which part the greatest amount of energy is being emitted.

b Explain why the hot radiator is emitting waves.

c Calculate the temperature of the radiator.

d Describe how the intensity versus wavelength graph will change as the radiator increases in temperature.

e Explain why the black-body spectrum of radiation gives evidence for quantised electron energy levels.

11 Light is shone on a sodium surface and photoelectrons are ejected. For a particular frequency, the stopping voltage is 1.4 V. The work function of sodium is 2.3 eV.

a Calculate the maximum velocity of the photoelectrons.

b Calculate the wavelength required.

12 Light from a star shines on a metal surface and produces photoelectrons. The work function of the metal is 1.22 eV. Determine the minimum temperature of the star.

13 Our Sun has an approximate surface temperature of 6000 K. If photons at the Sun's peak wavelength are impacting a metal surface and creating photoelectrons, what is the maximum work function (in eV) for that metal?

14 Calculate the momentum of a photon, produced at maximum wavelength from a 5778 K star like our sun (which can be assumed to be a black body). Use this momentum to determine how many photons need to hit a solar sail to impart 5.000 kg m s^{-1} of momentum to that sail.

15 A photon with a momentum of 3.31×10^{-27} kg m s^{-1}, impacts a metal surface which has a work function of 4.13 eV. What is the maximum kinetic energy (in joules) of the ejected photoelectron?

16 Bohr's condition applies to hydrogen and hydrogen-like species but also for other atoms in highly excited states known as Rydberg states where one electron is in an energy level much higher than the ground state configuration near ionisation. The kinetic energy of an electron occupying the $n = 60$ level of caesium is 3.89 eV. Determine the radius of the $n = 60$ energy level of caesium.

Topic 3: The Standard Model

Multiple choice

1 Select the correct statement about elementary particles from the following options.

A They are always strange.
B They are always neutral.
C They are all quarks, with a charge of $\frac{1}{3}$ or $\frac{2}{3}$.
D They are the fundamental building blocks of matter.

2 Select the option which best describes an antiparticle in relation to its equivalent particle.

A a particle with the same mass and electric charge but opposite spin
B a particle with the same magnetic properties but opposite electric charge
C a particle with the same charge, but opposite magnetic properties and spin
D a particle with the same mass but opposite electric charge and quantum numbers

3 Identify the correct list of quark names from the following options.

A up, down, left, right, top, bottom
B top, bottom, up, down, over, under
C up, down, top, bottom, strange, charm
D up, down, left, right, bottom, strange, charm

4 Select the list that names only leptons from the following options.

A tau, muon, electron, tau neutrino
B tau, muon, electron, photon, proton
C electron, positron, neutrino, proton, neutron
D tau neutrino, muon neutrino, electron neutrino, gluon

5 Select the statement that correctly describes gauge bosons from the following options.

A Gauge bosons are massless particles.
B Gauge bosons include gluons and photons.
C Gauge bosons are always neutral in charge.
D Gauge bosons are the same as Higgs bosons.

6 Select the statement that correctly describes elementary particles from the following options.

A Gluons interact with leptons.
B Quarks are subjected to the strong nuclear force.
C Leptons are subjected to the strong nuclear force.
D Quarks and leptons are both not subjected to the electromagnetic force.

7 From the following options identify the statement that describes one difference between baryons and mesons.

A Baryons are a subclass of leptons and mesons are a subclass of hadrons.
B Baryons are a subclass of hadrons and mesons are a subclass of leptons.
C Baryons are made up of a quark and an antiquark and mesons are made up of three quarks.
D Baryons are made up of three quarks and mesons are made up of a quark and an antiquark.

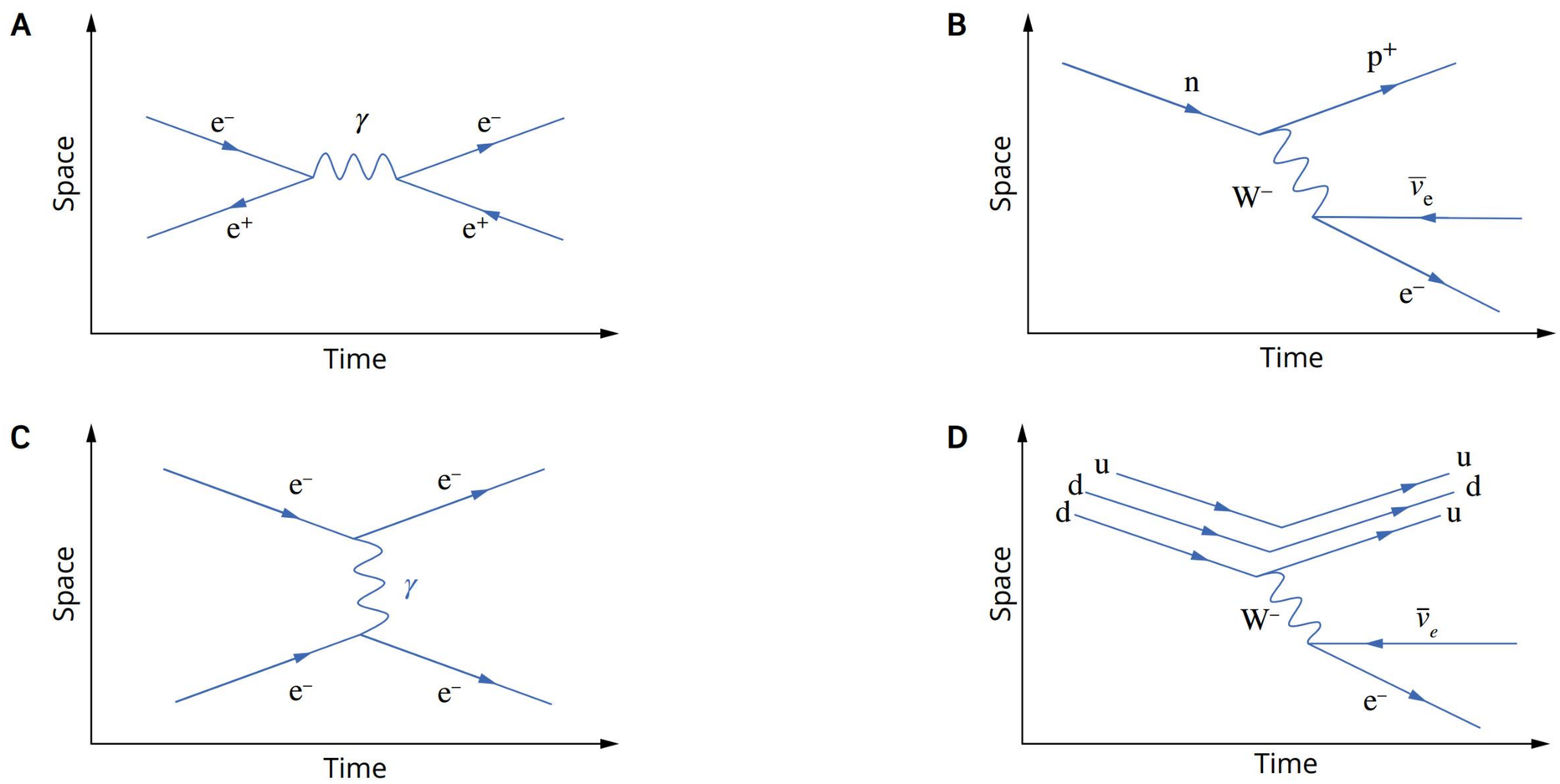
8 Select the correct statement about the baryon number of a particle from the following options.

A It is only conserved if the electric charge is conserved.
B It is only conserved if the initial baryon number is equal to 0.
C It is a conserved quantity that represents the net electric charge of the particles.
D It is a conserved quantity in which every quark has a baryon number of $+\frac{1}{3}$ and every antiquark has a baryon number of $-\frac{1}{3}$.

9 Select the correct statement about the lepton number of a particle.

A they come in six different flavours
B the lepton number of an electron is –1
C the lepton number of all baryons is zero
D the measure of the number of leptons in a system

10 Identify the particle interaction diagram below that depicts an electron and positron interaction.



Short answer

1 **a** The Standard Model explains three of the four fundamental forces in terms of an exchange of force-carrying particles called gauge bosons. Complete the table below for the four forces. Gravity has been completed as an example, but it is not part of the Standard Model.

Force	Nature of force	Range over which force acts (m)	Force carrier (gauge bosons)
	causes radioactive decay	10^{-18}	W^+, W^- and Z^0
electromagnetic			
	holds the nucleus of atoms together and acts between quarks	$\sim 10^{-15}$	
gravity	a force of attraction between any two objects with mass	infinite	graviton (theoretical and unobserved)

b Rank these four fundamental forces in order of their strength from strongest to weakest.

2 It was observed in the 1930s that when a neutron decayed, a proton and an electron were produced. It was consistently observed that the energy of the electron was less than expected. To avoid the violation of two fundamental principles of physics, Wolfgang Pauli suggested that another particle, undetectable at the time, was produced during neutron decay. This particle was later discovered and is now called an antineutrino.

Name the two fundamental principles of physics that would have been violated if an antineutrino was not produced during neutron decay.

3 State which one or more of the fundamental forces (strong nuclear, weak nuclear, electromagnetic and gravity) act on the following particles.

a proton
b electron
c neutron

4 A neutron is composed of two down quarks and one up quark. The mass of a neutron is greater than the sum of the masses of its component quarks. Explain this discrepancy in mass.

5 Name the two groups of hadrons and explain why they are separated.

6 Explain how a proton gains a +1 charge from its constituent quarks and explain how a neutron gains a neutral charge from its constituent quarks.

7 Explain the role of Symmetry in particle interactions.

8 Before the development of the Standard Model, it was thought that forces were exerted on particles by fields. In the Standard Model, it is believed that forces are exerted by the exchange of other particles.

a State the general name given to the particles that give rise to forces.
b Explain how the Standard Model accounts for the repulsion observed when two electrons approach each other.

9 There are six types of quarks in the Standard Model. Each quark also has its own antiquark. These are shown in Figure 11.2.2 in Chapter 11.

The lambda baryon, Λ_0, is composed of an up, a down and a strange quark. It has a rest mass of 1.98×10^{-27} kg and mean lifetime of 2.63×10^{-10} s.

a Show that the Λ_0 baryon has neutral electromagnetic charge.
b Calculate the mean lifetime of a Λ_0 baryon when it is travelling at 0.95c as measured in a laboratory.

10 **a** Complete the table below by filling in the name of each lepton.

Lepton	Lepton symbol	Antilepton symbol
	e^-	e^+
	ν_e	$\bar{\nu}_e$
	μ^-	μ^+
	ν_μ	$\bar{\nu}_\mu$
	τ^-	τ^+
	ν_τ	$\bar{\nu}_\tau$

b Determine whether the following decay for a muon is possible. Explain your answer.

$$\mu^- \rightarrow e^- + \nu_e$$

c Assume a muon decays to a combination of three leptons and antileptons. Using conservation of lepton number, electromagnetic charge and energy, describe what particles the muon could decay into.

11 Create the following particle interaction diagrams, and provide a description of the interaction with your answer.

a electron and electron
b electron and positron
c a neutron decaying into a proton

12 Determine if the following interactions are possible.

a $\pi^+ + p^+ \rightarrow p^+ + p^+ + \bar{n}$
b $p^+ + p^+ \rightarrow p^+ + p^+ + n$

Baryon number and lepton number conservation can determine the type of particle that is missing in an interaction. Complete the following questions for the particle interaction given below. Justify your responses.

$p^+ + p^+ \rightarrow p^+ + p^+ + X$

where X is an unknown particle

c Identify X as a baryon or a meson.
d State the electric charge of X.
e State whether X is a lepton or not.

In the following particle reaction, two unknown particles are produced.

$p^+ + p^+ \rightarrow p^+ + p^+ + X + Y$

Complete the following questions. Justify your answers.

f Identify which particles X and Y could be.
g State the electric charge of X and Y.
h State whether either X or Y could be a lepton.

13 Explain how the W^- boson mediating beta negative decay is a product of conservation of charge.

14 Buried beneath the surface of Antarctica is the IceCube Neutrino Observatory. It is a cubic kilometre in size and extends to a depth of about 2500 m to be large enough to have a chance of detecting neutrinos since their interactions are so rare. When neutrinos interact with the ice, they emit other particles which then emit Cherenkov light which can be detected by IceCube's very sensitive light sensors. Even at this size, IceCube detects about 275 neutrinos daily. Why are neutrinos so hard to detect?

15 Rhodium-106 decays into palladium-106 by beta negative decay. The binding energy of rhodium is 903.226 MeV and that of palladium is 906.300 MeV. If the mass of the electron emitted is 0.511 MeV, what is the kinetic energy produced in this decay?

Practical manual

Practical investigations support the development of science inquiry skills and provide you with hands-on experience to deepen your understanding. The following science inquiry investigations offer opportunities for you to engage with practical applications of scientific concepts. These skills involve identifying and posing questions and working to answer them, evaluating claims, investigating ideas, solving problems, reasoning, drawing valid conclusions, and developing evidence-based arguments.

Through these investigations, you will practice writing research questions, planning and conducting experiments, recording information, and reflecting on your processes. You will learn to process, analyse and interpret evidence, evaluate conclusions and claims critically, and communicate your findings effectively.

Syllabus subject matter

Unit 3: Gravity and electromagnetism

Practical investigation 1: Projectile motion—the effect of launch angle on range

- Investigate the horizontal distance travelled by an object projected at various angles from the horizontal.
- Interpret data relating to the horizontal distance travelled by an object projected at various angles from the horizontal.
- Solve problems involving projectile motion in the absence of drag effects using $v_y = u_y + gt$, $s_y = u_y t + \frac{1}{2}gt^2$, $v_y^2 = u_y^2 + 2gs_y$, $v_x = u_x$ and $s_x = u_x t$.
- Describe how horizontal and vertical components of a velocity vector are independent of each other.

Practical investigation 2: Investigating the force on a conductor in a magnetic field

- Investigate the force acting on a conductor in a magnetic field.
- Interpret data relating to the force acting on a conductor in a magnetic field.
- Solve problems involving the magnetic force on an electric current-carrying wire and moving charge in a magnetic field using $F = BIL\sin\theta$ and $F = qvB\sin\theta$.

Practical investigation 3: Investigating the strength of a magnetic field at various distances

- Investigate the strength of a magnet at various distances.
- Interpret data relating to the strength of a magnet at various distances.
- Solve problems involving the magnitude and direction of magnetic fields around a straight electric current-carrying wire and inside a solenoid using $B = \frac{\mu_0 I}{2\pi r}$ and $B = \mu_0 nI$.

Unit 4: Revolutions in modern physics

Practical investigation 4: Investigating the photoelectric effect

- Investigate variables related to the photoelectric effect such as:
  - photoelectron energy or velocity
  - electrical potential difference across the anode and cathode
  - wavelength or frequency of incident light
  - work functions of surfaces.
- Interpret data related to the photoelectric effect.

PRACTICAL INVESTIGATION 1

Projectile motion—the effect of launch angle on range

Forming and finding

Aim

To investigate the research question: What is the relationship between the launch angle and the horizontal range of a projectile?

Rationale

A projectile is any object that moves, without propulsion, in free flight. If air resistance is ignored, the only force acting on a projectile during its flight is that due to gravity. This force is constant and is always directed vertically downwards. It causes the projectile to follow a parabolic path.

The motion of a projectile can be examined by looking at the horizontal and vertical components separately.

Vertically, a projectile will move with an acceleration due to gravity ($9.8\,m\,s^{-2}$ downwards at the Earth's surface).

In the horizontal component, velocity is uniform since, if air resistance is ignored, there are no forces acting in this direction.

If a projectile is launched at an angle to the horizontal, trigonometry can be used to find the initial horizontal and vertical components of the velocity. The equations of motion can then be used to calculate the horizontal distance travelled by the projectile.

Timing

40 minutes

Materials

- data-collection system
- projectile launcher (commercial or improvised, e.g. poly tube)
- projectile
- photogates and (optionally) a time-of-flight pad or stopwatch
- angle indicator
- tabletop or bench
- table clamp or burette stand and clamps
- A4 paper
- tape measure
- sticky tape
- carbon paper (optional)

Safety

Always wear safety glasses when using any kind of projectile launcher. Never look down the barrel of a mechanical projectile launcher.

Method

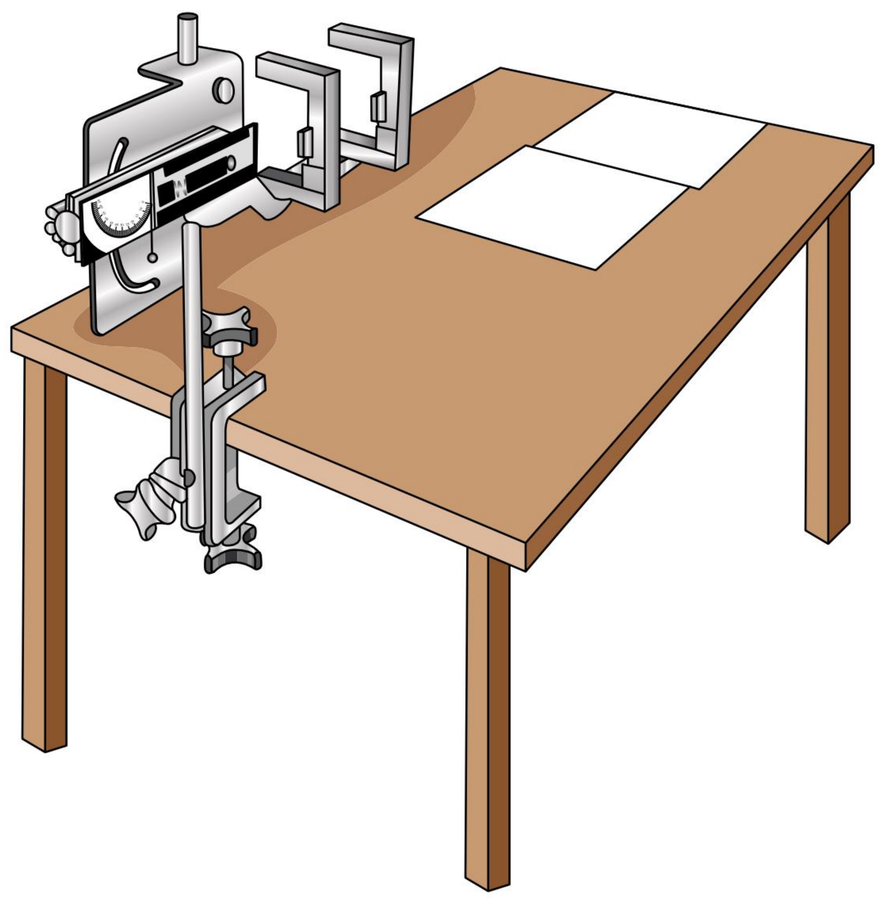
Risk assessment

Before you commence this practical activity, you must conduct a risk assessment.

➤ Reflect and check the material and method for risks

- consider and account for risks/ethical issues/environmental issues in the materials and method
- conduct a risk assessment, completing the template in your Skills and Assessment book or downloading it from your eBook

1. Start a new experiment on your data-collection system. Connect the photogates to your system following the manufacturer's instructions.
   Note: If photogates aren't available to you, a stopwatch can be used to find the flight time. In estimating the uncertainty in the measurement, be sure to allow for your reaction time when both starting and stopping the watch.
2. Select 'velocity between gates' if prompted by your data-collection system.
   Ensure the 'space between gates' parameter on your data-collection system is set to the measured space between your photogates.
3. Attach the projectile launcher to a table so that the projectiles travel across the longest part of the table. One suitable arrangement of launcher, photogates and table is shown in the set-up below. Use the equipment available to you to arrange the launcher to 'fire' down the length of the table and through the photogates. Be careful to avoid firing the projectile near classmates.



If a spring-loaded projectile launcher isn't available to you, a piece of curved 'poly pipe' supported by a retort stand can make a good alternative. Discuss, with the aid of diagrams, how you could do this.

4 Place sheets of paper end-to-end in a line across the length of the table in front of the projectile launcher, and secure them in place with tape.

5 Measure the height from the point the ball is released to the tabletop, and record this value in the Analysing section.

6 Mount the photogates on the launcher. Be sure to mount the first named photogate in your data-analysis software closest to the launcher.

Part 1—Distance versus angle

7 Set the launcher in the horizontal position with a launch angle of 0°. Record an estimate of the uncertainty in the measurement of the angle in the Analysing section.

8 Load a projectile into the launcher, and ensure that the launcher is set to its maximum compression or distance setting.

9 Lay a sheet of carbon paper on top of the white paper over the point of impact, carbon side down, so that when a ball lands on it there will be a mark on the paper. Place a sheet of paper over the carbon paper to prevent damage to the carbon paper by the projectile.

If carbon paper is not available, look for a small indentation on the paper where the ball hits or use tracing paper heavily shaded with lead pencil. Highlight the point with a pencil or marker when the projectile lands. Another option is to use a shallow tub of sand.

What launch angle do you predict will yield the greatest horizontal range (distance)?

10 Start recording with the data collection system (or your stopwatch) and launch the projectile.

Record the sampled 'velocity between gates' data point or time of flight and enter the corresponding angle value in Table 1 in the Analysing section.

11 Launch the projectile and note the point of impact on the paper.

12 Move the carbon paper and measure the distance to the mark from the base of the launcher. Write the angle next to the mark on the paper.

13 Use the angle indicator on the launcher to position the launcher at the next angle, 10°.

14 Repeat the data collection steps, increasing the angle of inclination by 10° each time until you have recorded a data point every 10° from 0° to 80°.

15 Repeat the measurement for each angle an additional two times, and find the average and uncertainty in the range.

16 Measure and enter the horizontal distance for each angle value into Table 1 in the Analysing section. Draw a graph of distance versus angle and a graph of velocity versus angle in the spaces provided.

Part 2—Time of flight

17 If a time-of-flight pad is available, remove one photogate and attach the time-of-flight pad. Alternatively, a handheld stopwatch or other timing mechanism can be used. Position the time-of-flight pad over the landing point recorded for an angle of 0° and reset the launcher to an angle of 0°.

Which angle do you think will give the greatest time of flight? Explain the reasons behind your prediction.

18 Start a new data-collection session. Launch the ball from the launcher and, using the time-of-flight pad or a stopwatch, record the time the ball is in flight in Table 2 of the Analysing section.

19 Use the angle indicator on the launcher to position the launcher at the next angle, and repeat the data-collection steps until you have recorded a data point every 10° from 0° to 80°. Record the time of flight for each angle in Table 2 of the Analysing section. Repeat each angle three times, and find the average time and uncertainty in the range for each angle. Draw a graph of time of flight versus angle.

Variables

- independent: launch angle
- dependent: range of projectile
- controlled: projectile shape, projectile mass, force of launch

Analysing

Raw and processed data

Height above the tabletop the ball is released: _____

TABLE 1 Projectile data for launch angle versus distance

Angle (°) ±	Velocity ($m\,s^{-1}$)				Distance (m)			
	Trial 1	Trial 2	Trial 3	Average	Trial 1	Trial 2	Trial 3	Average
				±				±
				±				±
				±				±
				±				±
				±				±
				±				±
				±				±
				±				±

TABLE 2 Projectile data for launch angle versus time of flight

Angle (°) ±	Time of flight (s)			
	Trial 1	Trial 2	Trial 3	Average
				±
				±
				±
				±
				±
				±
				±

➤ Reflect and check that your data analysis demonstrates these characteristics

- collection of sufficient and relevant raw data
- correct and relevant processing of data
- fluent and concise use of scientific language and representations

Analysis

1 Choose one of the angles other than 0° and draw to scale a vector diagram for your projectile at the launch position showing both the horizontal and vertical component velocities. Show how you would determine the average initial velocity and draw the net vector.

2 Calculate the horizontal and vertical components of velocity for each angle and complete the columns in Table 3.

3 Use the horizontal distance and time of flight to calculate the average horizontal velocity for each angle and fill in the corresponding column in Table 3. Why is this referred to as the *average* horizontal velocity?

4 Use the vertical velocity and the height of the launcher for each launch angle to calculate the theoretical time of flight of an object shot straight up. Record the results in Table 3.

Interpreting and evaluating

Conclusion

1 How did the measured horizontal velocities from Table 1 compare to the calculated horizontal velocities from Table 3?

2 For any projectile launched horizontally, what can you state about the horizontal velocity?

3 Which launch angle will yield the maximum horizontal range?

Evaluation

4 Consider whether the reliability with which you could set and measure the angle of launch permitted reasonable conclusions to be drawn in this experiment. Discuss the effect of the uncertainty in your method on the reliability of your conclusion.

TABLE 3 Projectile data calculations

Angle (°)	Horizontal velocity ($m\,s^{-1}$)	Vertical velocity ($m\,s^{-1}$)	Average horizontal velocity ($m\,s^{-1}$)	Theoretical time of flight (s)

➤ Reflect and check that your analysis demonstrates these characteristics

- thorough and appropriate identification of the uncertainty and limitations of evidence
- thorough identification of relevant trends/patterns/relationships
- justified conclusion/s linked to the research question

Improvements

5 Identify the major sources of error in this experiment and the steps taken to minimise them.

Extension

6 Are there launch angles that yield the same horizontal range? What are they and why is that the case?

➤ Reflect and check that your evaluation demonstrates these characteristics

- thorough and appropriate identification of the uncertainty and limitations of evidence
- justified discussion of the reliability and validity of the experimental process
- suggested improvements and extensions to the experiment that are logically derived from the analysis of evidence

Investigating the force on a conductor in a magnetic field

Forming and finding

Aim

To investigate the research question: What is the relationship between the current in a current-carrying wire and the force on the current-carrying wire in a constant magnetic field?

Rationale

A current-carrying wire will experience a force when placed in a magnetic field.

The force, F, experienced by the wire is given by $F = BIL\sin\theta$, where I is the current in the wire (A), L is the length of the wire (m), θ is the angle between the conductor and the magnetic field, and B is the strength of the magnetic field (T).

By varying the current through a wire placed perpendicularly in a magnetic field of known constant strength and measuring the force experienced by the wire using a balance, a relationship between force and current can be found. By placing the conductor perpendicular to the magnetic field, $\sin\theta$ will be equal to 1, allowing for direct investigation of the relationship between force and current.

Timing

30 minutes

Materials

- commercial current balance or copper wire (at least 4.00 m) to construct same
- electronic balance (0.1 g resolution or better)
- variable DC power supply
- ammeter or current sensor
- permanent magnets (preferably a strong horseshoe magnet)

Safety

- Make sure the ammeter is set up correctly (in series) in your circuit.
- Do not allow current to flow through the wires for any longer than a few seconds. The wires (and possibly the power supply) can become hot, and cause burns and damage equipment. Do not exceed 1 A.

Method

Risk assessment

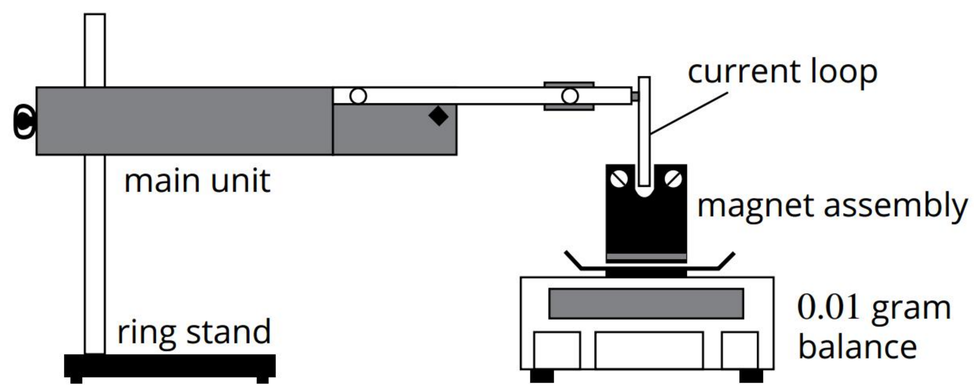
Before you commence this practical activity, you must conduct a risk assessment.

➤ Reflect and check the material and method for risks

- consider and account for risks/ethical issues/environmental issues in the materials and method
- conduct a risk assessment, completing the template in your Skills and Assessment book or downloading it from your eBook

1 Set up the commercial current balance following the manufacturer's instructions. The diagram below shows a typical arrangement of current balance and electronic balance. Consult your manufacturer's instructions for the appropriate arrangement for your apparatus.

A similar balance can be made if a commercial balance is not available. Wind copper wire into a square of 5.0 cm by 5.0 cm at least 10 times. If using copper wire, check if it is enameled, and remove coating using sandpaper to ensure a closed circuit. Place the horseshoe magnet on the electronic balance with the north and south poles facing up. Stand the 10 loops of copper wire on a retort stand so that it hangs with one edge exactly parallel to, and between the N and S poles of the horseshoe magnet. Zero/tare the balance.



2 Change the current flowing through the wire, I, by varying the voltage, V. Measure the reading on the balance for five different values of I. Be careful to keep the current below 1 A or at least within the range of your ammeter or sensor. Select an appropriate measurement uncertainty for current to account for any variation in current.

3 The force acting on the wire is due to the interaction between the magnetic field of the horseshoe magnet and the magnetic field generated by the current flowing through the wire. The balance will read either a positive or negative value, depending on the direction

of the current. The value displayed on the balance is the equivalent of how much the 'mass' of the wire has changed, i.e. the force recorded in the table opposite will be equal to the mass displayed multiplied by 9.8 (the acceleration due to gravity).

4 Note the results in a table for current through the wire and force exerted on the current balance, with the uncertainty for each measurement. The uncertainty in the measurement for the current is likely to be ±0.1 A (but please determine this for your apparatus) and the uncertainty in the measurement for the change in mass exerted on the current balance is always ± 1 of the smallest decimal displayed. Refer to Chapter 1 for a reminder of how to determine the uncertainties in a measurement.

5 Repeat the same measurements at least two more times in order to obtain an average.

6 Repeat steps 3–5 for a total of at least five different values of current.

Variables

- independent: the current, *I*, flowing through the wire
- dependent: the force, *F*, experienced by the wire in the magnetic field
- controlled: magnetic field, length of wire

Analysis

1 Plot the results from Table 1 on a graph, with the independent variable (*I*) on the *x*-axis and the dependent variable (*F*) on the *y*-axis. Include error bars for each point plotted.

2 Draw a line of best fit. Use your error bars to draw minimum and maximum lines.

3 Calculate the uncertainty in the gradient.

4 Identify any points on your graph that do not fit the trend. Explain why this may be the case.

5 Determine the gradient of the line of best fit. Using $F = BIL\sin\theta$. If the magnet was placed perpendicularly to the field in your experiment, $\sin\theta$ will be equal to 1, making the gradient equal to *BL*.

6 Measure the value of *L*, which is the *total* length of wire that passes through the gap between the north and south poles of the horseshoe magnet (not the entire length of the wire). Determine the uncertainty in *L*.

7 Use the gradient and value of *L* to determine the value of *B*, which is the strength of the horseshoe magnet. Also calculate the uncertainty in *B* using the uncertainties in the gradient and *L*.

8 Compare your graph with the graphs drawn by other groups who used different values for current, and magnets of different size and strength. Describe what you notice about the shapes of the graphs.

Analysing

Raw and processed data

TABLE 1 Measured force experienced by a wire in a magnetic field

Current, *I* (± ___ A)	**Measured change in mass, *m* (± ____ kg)**				**Calculated force, *F* (± _____ N)**			
	Trial 1	**Trial 2**	**Trial 3**	**Average**	**Trial 1**	**Trial 2**	**Trial 3**	**Average**
				±				±
				±				±
				±				±
				±				±
				±				±
				±				±
				±				±

➤ Reflect and check that your data analysis demonstrates these characteristics

- collection of sufficient and relevant raw data
- correct and relevant processing of data
- fluent and concise use of scientific language and representations

9 Explain whether you expected the graphs to be the same or different.

10 Compare the value, and uncertainty, of the strength of the horseshoe magnet with other groups. Discuss any consistency in the results.

> ➤ **Reflect and check that your analysis demonstrates these characteristics**
>
> - thorough and appropriate identification of the uncertainty and limitations of evidence
> - thorough identification of relevant trends/patterns/relationships
> - justified conclusion/s linked to the research question

Interpreting and evaluating

Conclusion

1 Discuss whether you were able to definitively answer the research question, including if your results adhered to the formula $F = BIL\sin\theta$.

2 State your final value of the strength of the magnetic field of the horseshoe magnet and the value's uncertainty.

Evaluation

3 Considering your analysis and conclusion, discuss whether the experiment provided an effective method of measuring the force experienced by the current-carrying wire.

4 Consider whether the level of uncertainty that you calculated in step 7 of Analysis was reasonable.

Improvements

5 If you were to repeat the experiment, propose what you would do differently.

Include in your answer:

- how you would change the methodology and how this might improve the results
- what skills you used to perform the tasks and how your technique could be improved
- how the collection of data could be made more reliable and the uncertainty reduced.

Extension

1 Determine whether this experiment would work using any magnet.

2 Identify any limitations to using this method for other magnets.

3 Outline how this method could be used to determine the strength and direction of Earth's magnetic field.

4 For this experiment, the current-carrying wire is placed parallel to the poles of the magnet. Explain the change in the force of placing the current-carrying wire at an angle to the magnet.

> ➤ **Reflect and check that your evaluation demonstrates these characteristics**
>
> - thorough and appropriate identification of the uncertainty and limitations of evidence
> - justified discussion of the reliability and validity of the experimental process
> - suggested improvements and extensions to the experiment that are logically derived from the analysis of evidence

Investigating the strength of a magnetic field at various distances

Forming and finding

Aim

To investigate the research question: What is the relationship between magnetic field strength and distance from a wire carrying constant current?

Rationale

The strength of the magnetic field around a current-carrying wire varies with the distance from the wire according to:

$$B = \frac{\mu_0 I}{2\pi r}$$

where B is the magnetic field strength, μ_0 is the magnetic constant, I is the current flowing through the wire and r is the distance from the wire.

Timing

30 minutes

Materials

- copper wire
- ammeter or current sensor
- variable DC power supply
- 30 cm ruler
- resistor
- magnetic field sensor or magnetic field app for a smartphone
- clamp stand and clamp

Safety

- Make sure the ammeter is set up in series in your circuit.
- Do not allow current to flow through the wires any longer than a few seconds. The wires (and possibly the power supply) can become hot, and cause burns and damage equipment. Keep the current below 1 A.

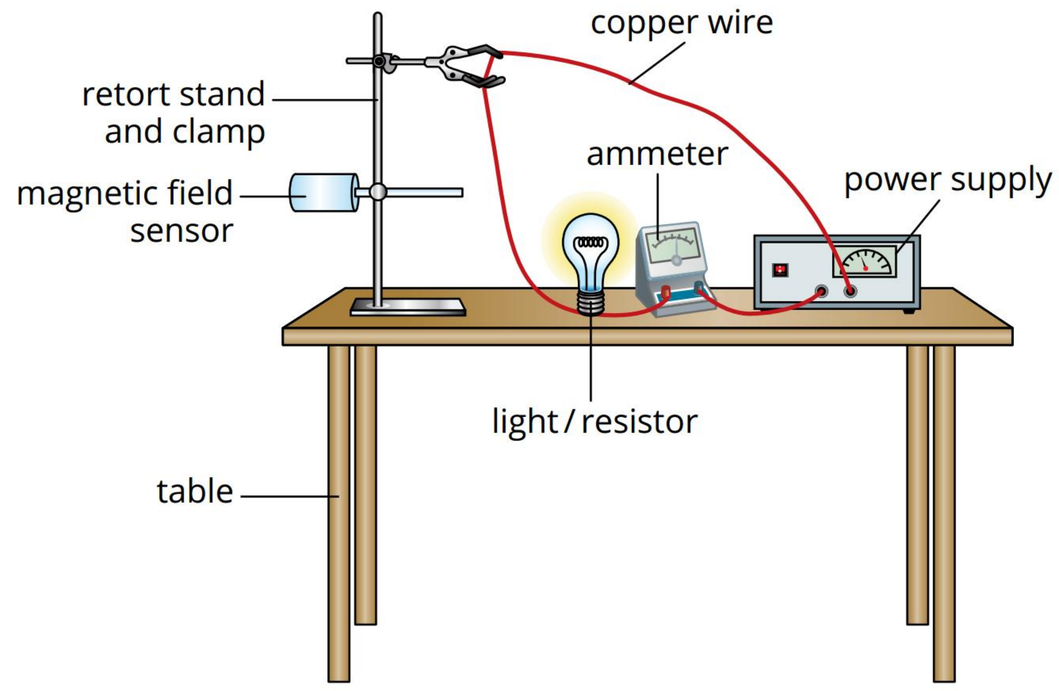
Method

Risk assessment

Before you commence this practical activity, you must conduct a risk assessment.

➤ Reflect and check the material and method for risks
• consider and account for risks/ethical issues/environmental issues in the materials and method • conduct a risk assessment, completing the template in your Skills and Assessment book or downloading it from your eBook

1 Set up a circuit using the variable power supply, the copper wire, the resistor and the ammeter. Attach the copper wire to the clamp on a retort stand placed at the end of a table so that one end of the wire hangs down to the table but at an angle to the table. Connect the other end of the wire to the power supply. If using copper wire, check if it is enameled, and remove coating using sandpaper to ensure a closed circuit. The circuit is completed by connecting the two ends of the wire via a resistor and power supply.



2 Turn on the power supply. Note down the value of I on the ammeter or current sensor. Select an appropriate measurement uncertainty for current to account for any variation in current. Measure the magnetic field at five perpendicular distances from the wire using the magnetic field sensor.

3 Note the results in a table for distance from the copper wire and magnetic field strength, with the uncertainty for each measurement. The uncertainty in the measurement for the distance is likely to be ±0.5 cm, and the uncertainty in the measurement for magnetic field strength is determined by the instrument you are using. Refer to Chapter 1 for a reminder of how to determine uncertainties in a measurement.

4 Repeat the measurements twice in order to obtain an average.

Variables

- independent: the distance, r, from the conductor
- dependent: the magnetic field strength, B
- controlled: the current, I, flowing through the wire

Analysing

Raw and processed data

TABLE 1 Measured magnetic field strength at different distances from a current-carrying wire

Distance, r (± _____ m)	Measured magnetic field strength, B (± _____ T)			
	Trial 1	Trial 2	Trial 3	Average
				±
				±
				±
				±
				±

TABLE 2 Measured magnetic field strength and the reciprocal of the distance

Reciprocal of Distance, $\frac{1}{r}$ (± ____ m^{-1})	Measured magnetic field strength, B (± _____ T)			
	Trial 1	Trial 2	Trial 3	Average
				±
				±
				±
				±
				±

➤ Reflect and check that your data analysis demonstrates these characteristics

- collection of sufficient and relevant raw data
- correct and relevant processing of data
- fluent and concise use of scientific language and representations

Analysis

1. Plot the results from Table 1 on a graph, with the independent variable r on the x-axis and the dependent variable B on the y-axis. Include error bars for each point plotted.
2. Describe the shape of this graph.
3. Plot the results from Table 2 on a graph, with the reciprocal of the independent variable, $\frac{1}{r}$, on the x-axis and the dependent variable B on the y-axis. Include error bars for each point plotted.
4. Draw a line of best fit. Use the error bars to draw a minimum and maximum line.
5. Identify any points on your graph that do not fit the trend. Explain why this might have been the case.
6. Calculate the gradient of the line of best fit. Using $B = \frac{\mu_0 I}{2\pi r}$, the gradient is equal to $\frac{\mu_0 I}{2\pi}$. Use the measured value for I and the value of π to calculate the value of μ_0.
7. Use the uncertainty in the gradient and the uncertainty in I to calculate the uncertainty in μ_0.
8. Compare your graph to the graphs drawn by other groups who used different values for current. Describe what you notice about the shape of the graphs.
9. Compare your value of μ_0 with other groups.
10. Discuss whether you would expect your results to be the same or different.

➤ Reflect and check that your analysis demonstrates these characteristics

- thorough and appropriate identification of the uncertainty and limitations of evidence
- thorough identification of relevant trends/patterns/relationships
- justified conclusion/s linked to the research question

Interpreting and evaluating

Conclusion

1 The aim of the experiment was to investigate the strength of the magnetic field from a current-carrying wire at various distances. State the relationship you found between the distance from the conductor and the magnetic field strength. Consider whether your results fit the formula $B = \frac{\mu_0 I}{2\pi r}$. State your value for μ_0 with its uncertainty.

Evaluation

2 Considering your analysis and conclusion, discuss whether the experiment provided an effective method of measuring the magnetic field strength at various distances.

3 Consider whether the level of uncertainty that you calculated in step 7 of Analysis was reasonable.

Improvements

4 If you were to repeat the experiment, propose what you would do differently.

Include in your answer:

- how you would change the methodology and how this might improve the results
- what skills you used to perform the tasks and how your technique could be improved
- how the collection of data could be made more reliable and the uncertainty reduced.

Extension

5 Consider if this experiment would work if you measured the distance from the wire in any direction, other than perpendicular to the wire.

6 Identify any limitations to using this method for other distances from the wire.

➤ Reflect and check that your evaluation demonstrates these characteristics

- thorough and appropriate identification of the uncertainty and limitations of evidence
- justified discussion of the reliability and validity of the experimental process
- suggested improvements and extensions to the experiment that are logically derived from the analysis of evidence

Investigating the photoelectric effect

Forming and finding

Aim

To investigate the research questions:

- What is the relationship between current and intensity for a light source of constant frequency in the photoelectric effect?
- What is the relationship between frequency of a light source and stopping voltage in the photoelectric effect?

Rationale

The 'photoelectric effect' refers to the emission of electrons from the surface of a metal when light of low wavelength is incident on the surface. This phenomenon cannot be sufficiently explained using the wave theory of light, and its explanation led to the development of the photon or particle-like dual-nature model of light we have today.

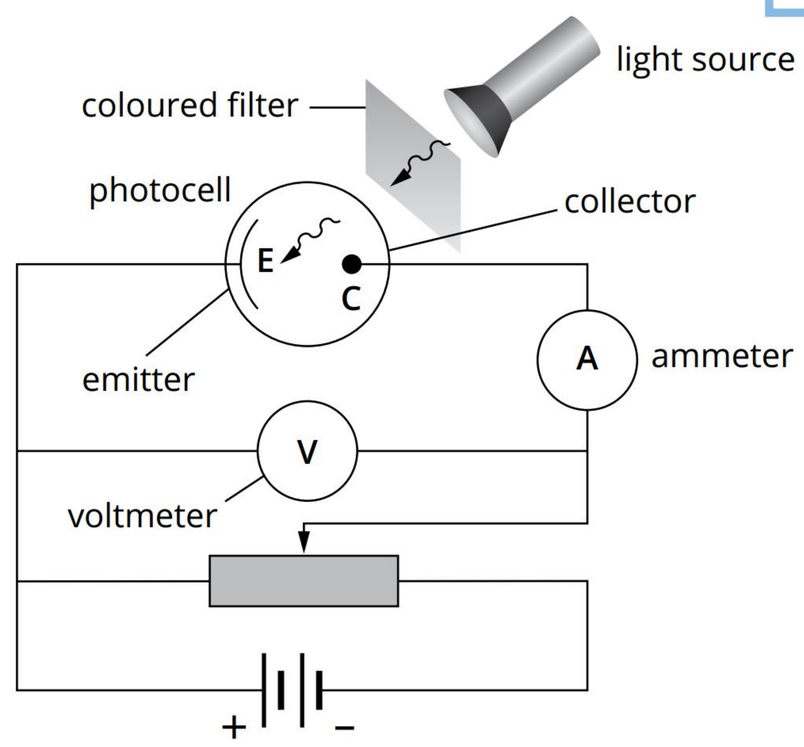
In the photon model, a beam of light consists of a stream of photons, each carrying an energy, $E = hf$, where h is Planck's constant (6.626×10^{-34} J s) and f is the frequency of the incident light (Hz).

The work function, W, for the metal is given by $W = hf_0$, where f_0 is the threshold frequency and is different for each metal. If the frequency of the incident light is greater than the threshold frequency, then a photoelectron will be ejected with some kinetic energy up to a maximum value such that $E_k = hf - W$.

This can be explored experimentally using the apparatus shown in the diagram on the right. If light is incident on the cathode, the photoelectrons emitted will be collected at the anode and registered as a photocurrent, which can be measured.

The maximum kinetic energy for the electrons (i.e. the fastest electron) can be found using a reverse voltage called the stopping voltage, V_s, using $E_k = W = q_eV_s$.

Refer to Chapter 9 for a reminder of the relationships detailed above.



Timing

45 minutes

Materials

- photoelectric effect kit
- current detector and amplifier, or current sensor and interface
- lamp to suit kit (incandescent, fluorescent or mercury vapour)
- set of coloured filters
- voltmeter or voltage sensor
- electrical leads

Safety

If you are using a mercury lamp, avoid looking directly at it. It is advisable to wear protective glasses.

Method

Risk assessment

Before you commence this practical activity, you must conduct a risk assessment.

➤ Reflect and check the material and method for risks
• consider and account for risks/ethical issues/environmental issues in the materials and method • conduct a risk assessment, completing the template in your Skills and Assessment book or downloading it from your eBook

The diagram above shows a typical circuit for a photoelectric effect kit. Check the instructions with your kit for the particular circuit that applies.

1 Set up the circuit as shown in the diagram, following any directions that are specific to your kit. (You may find most or all of the circuit is built into the kit.)

The relative positions of the light source and the photocell should stay fixed. Start with the filter that transmits the longest wavelength of visible light (usually red).

2 Using the first filter, take a series of readings of I and V. Record your readings in a suitable table with an uncertainty for each reading.

V is negative because it is the stopping voltage, slowing down the electrons as they are emitted.

Start with small voltages (0.1 V). Take care to carefully note the stopping voltage, V_s (i.e. when the current *first* reaches zero). Repeat the approach to zero current a few times, increasing the sensitivity of the current reading (if possible with your kit) and average your results for V_s.

3 Increase the intensity of the light source and take readings of I and V. Once again determine V_s.

This should be the same as previously measured, since V_s is independent of light intensity.

4 Replace the red filter with the filter with the next longest wavelength available. For this filter, determine only the stopping voltage. Repeat the approach to zero current a few times, each time increasing the sensitivity of the current reading (if possible with your kit) and average your results for V_s.

5 Repeat step 4 with the remaining filters and tabulate the frequency, f, of each filter and the stopping voltage, V_s, with the uncertainties for each value.

Variables

- independent: voltage, V
- dependent: current, I
- controlled: frequency of light, f (controlled using coloured filters), intensity of light, type of metal of cathode

Analysing

Raw and processed data

TABLE 1 Measured photocurrent with different voltages

Incident light colour: red

Intensity 1: _____

Voltage, V (± _____ V)	Measured current, I (± _____ μA)			
	Trial 1	Trial 2	Trial 3	Average
±				±
±				±
±				±
±				±
±				±

TABLE 2 Measured photocurrent with different voltages

Incident light colour: red

Intensity 2: _____

Voltage, V (± _____ V)	Measured current, I (± _____ μA)			
	Trial 1	Trial 2	Trial 3	Average
±				±
±				±
±				±
±				±
±				±

➤ Reflect and check that your data analysis demonstrates these characteristics

- collection of sufficient and relevant raw data
- correct and relevant processing of data
- fluent and concise use of scientific language and representations

Analysis

1 From the data in Tables 1 and 2, draw a graph with V on the x-axis and I on the y-axis. Clearly mark the different intensity for each set of data, and the stopping voltage, V_s. Did you get the same value for the stopping voltage for both intensities of light? Did your graph look like Figure 9.3.2 on page 245?

2 Calculate $E_k = q_e V_s$, which corresponds to the maximum kinetic energy of the photoelectrons (in eV) as they left the surface of the emitter, for each frequency tested. Enter the values in Table 3. If your photoelectric-effect kit does not give the frequency for each filter, look up the frequency of light.

TABLE 3 Measured stopping voltage for different colour incident light

Colour of incident light	Frequency of incident light	Measured stopping voltage, V_s (± _____ V)				$E_{k\,max}$
		Trial 1	Trial 2	Trial 3	Average	
					±	
					±	
					±	
					±	
					±	

3 Draw a graph of f (on the x-axis) against E_k (on the y-axis).

4 The maximum kinetic energy of the electrons is given by $E_k = hf - W$, which is the same format as the equation for a straight line, $y = mx + c$. From your graph, determine:

a the work function, W (the point where the line crosses the y-axis) and its uncertainty

b Planck's constant (the gradient of the line) and its uncertainty

c the threshold frequency, f_0, for the metal of the cathode, and its uncertainty. This will be the point where the line crosses the x-axis, i.e. where $E_k = 0$.

➤ **Reflect and check that your analysis demonstrates these characteristics.**

- thorough and appropriate identification of the uncertainty and limitations of evidence
- thorough identification of relevant trends/patterns/relationships
- justified conclusion/s linked to the research question

Interpreting and evaluating

Conclusion

1 The aim of the experiment was to investigate the photoelectric effect. Summarise your results for the quantities found.

2 State the single most important contribution of the photoelectric effect to our understanding of the nature of light.

3 In the first part of the experiment, a lower current was obtained with a less intense light. Explain this in terms of a particle model of light.

4 Explain why the stopping voltage depends only on the frequency of the incident light and not on the intensity.

Evaluation

5 Considering your analysis and conclusion, did the experiment provide an effective method of exploring the photoelectric effect, and measuring the stopping voltage, threshold frequency and work function of the cathode? Was your value of Planck's constant close to the established value of 4.14×10^{-15} eV s? (Remember that the value for E_k was calculated in eV, so your value of Planck's constant will also use eV, not J.)

6 Was the level of uncertainty that you calculated in part 4 of the Analysis section reasonable?

Improvements

7 If you were to repeat the experiment, what would you do differently?

Include in your answer:

- how you would change the methodology and how this might improve the results
- what skills you used to perform the tasks and how your technique could be improved
- how the collection of data could be made more reliable and the uncertainty reduced.

Extension

8 Could you identify the metal used in the cathode from your results?

9 Would this experiment work using any metal for the cathode?

10 Identify any limitations to using this method for other metals.

➤ **Reflect and check that your evaluation demonstrates these characteristics.**

- thorough and appropriate identification of the uncertainty and limitations of evidence
- justified discussion of the reliability and validity of the experimental process
- suggested improvements and extensions to the experiment that are logically derived from the analysis of evidence

Science as a human endeavour

Science as a human endeavour (SHE) features develop foundational skills that support scientific inquiry. They provide essential stimulus for the research investigation, providing a foundation for you to launch into your own research investigation (IA3) and build proficiency in assessment objectives 1, 2 and 3. The SHE features provide practise in writing research questions, planning and conducting experiments, recording information, and reflecting on processes. You will learn to process, analyse, and interpret evidence, evaluate conclusions and claims critically, and communicate your findings effectively.

Syllabus subject matter

Unit 3: Gravity and electromagnetism

Science as a human endeavour 1: Hunting exoplanets

- Appreciate the significant contributions of scientists such as Isaac Newton, Johannes Kepler, Émilie du Châtelet and Katherine Johnson who furthered our understanding of gravity and motion.
- Explore how technologies such as satellites have dramatically increased the size, accuracy, and geographic and temporal scope of datasets with which scientists work.

Science as a human endeavour 2: Gravitational waves and the Australian connection

- Explore the international collaboration required in the discovery of gravity waves and associated technologies, e.g. Laser Interferometer Gravitational Wave Observatory (LIGO).

Science as a human endeavour 3: Artificial satellites and space junk

- Consider the factors that contribute to positioning of satellites used for observation of weather, natural phenomena, traffic and military movements.
- Consider the international collaboration required to monitor the orbits of satellites, and the management of space debris.
- Explore how technologies such as GPS and ring laser gyroscopes (RLG) assist with accurate navigation and consider the ethics surrounding their use.

Science as a human endeavour 4: Models of the universe

- Consider the difference between the heliocentric and geocentric models of the solar system.
- Appreciate how the accepted model of the solar system slowly shifted under the influence of carefully collected and analysed data.
- Appreciate the significant contributions of scientists such as Isaac Newton, Johannes Kepler, Émilie du Châtelet and Katherine Johnson who furthered our understanding of gravity and motion.
- Explore the difficulties experienced by scientists who supported a heliocentric model of the solar system and the hindrances to the acceptance of their discoveries by society.

Science as a human endeavour 5: Solar storms

- Consider the scientific evidence concerning the risks of electromagnetic phenomena and associated technologies (e.g. wi-fi and mobile phones) as reported in the media.
- Consider the international collaboration required to monitor the orbits of satellites, and the management of space debris.

Science as a human endeavour 6: Superconductivity

- Explore the discoveries and theories that led to our current understanding of superconductivity.

Unit 4: Revolutions in modern physics

Science as a human endeavour 7: The dual characteristics of light

- Appreciate the significant contributions of scientists such as Wilhelm Wien, Max Planck, Ernest Rutherford, Niels Bohr, Maria Goeppert-Mayer and Johannes Rydberg who furthered our understanding of quantum theory.
- Explore the historical development of the model of the atom in terms of traditional models.
- Consider how theories are contested, refined or replaced when new evidence challenges them, or when a new model or theory has greater explanatory power.

Science as a human endeavour 8: The Large Hadron Collider and the Higgs boson

- Examine evidence supporting theories related to particle physics.
- Appreciate the significant contributions of scientists such as Chien-Shiung Wu, Richard Feynman and Peter Higgs who furthered our understanding of particle physics and The Standard Model.
- Explore the history of particle physics models and theories through the development of particle accelerators and contributions from notable physicists.
- Appreciate that particle accelerators like the Australian Synchrotron and Large Hadron Collider are developed through multinational collaborations between science organisations and governments.
- Appreciate the contribution of Australian scientists to the discovery of the Higgs boson.
- Explore the evidence relating to the Standard Model that supports the Big Bang theory.

Science as a human endeavour 9: The Hafele–Keating experiment

- Consider the experimental evidence that supports the phenomena of time dilation and its real-world applications.
- Appreciate the significant contributions of scientists such as Albert Einstein and Amalie 'Emmy' Noether who furthered our understanding of relativity.
- Explore how special relativity built upon the work of previous scientists and led to the development of relativistic theories of gravitation, mass–energy equivalence and quantum field theory.

Science as a human endeavour 10: Noether's theorem

- Appreciate the significant contributions of scientists such as Albert Einstein and Amalie 'Emmy' Noether who furthered our understanding of relativity.

- Explore how special relativity built upon the work of previous scientists and led to the development of relativistic theories of gravitation, mass–energy equivalence and quantum field theory.
- Consider how theories are contested, refined or replaced when new evidence challenges them, or when a new model or theory has greater explanatory power.
- Describe how symmetry in particle interactions occurs to maintain the principles of conservation.
- Appreciate the significant contributions of scientists such as Chien-Shiung Wu, Richard Feynman and Peter Higgs who furthered our understanding of particle physics and The Standard Model.
- Explore the history of particle physics models and theories through the development of particle accelerators and contributions from notable physicists.

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Hunting exoplanets

In recent years, scientists have been interested in discovering planets like those in Earth's solar system. One way these extrasolar planets (or exoplanets) are detected is by the gravitational effect they have on their host star. When any planet orbits a star, it causes the star to measurably 'wobble'. At the time of writing there are more than 5000 known exoplanets, some of which were discovered using this technique.

Consider the law of universal gravitation: $F = \frac{GMm}{r^2}$. You will see that the larger the mass of the planet (m), the greater the gravitational force (F) between that planet and its host star (M), causing the host star to wobble. The inverse square relationship to distance $\left(F \propto \frac{1}{r^2}\right)$ means that the closer the planet's orbit (r) is to the star, the greater the wobble. This means the easiest exoplanets to find are those known as 'hot Jupiters'—planets the mass of Jupiter or larger, and orbiting their star closer than Mercury orbits the Sun. These planets exert detectable forces on their host star.

These hot Jupiters were the first exoplanets to be discovered using the gravitational wobble method. Prior to this, astronomers didn't believe planets this large could form so close to a star. In 1995 the exoplanet Dimidium (51 Pegasi b) was discovered using this method. In 2019 the astronomers Michel Mayor and Didier Queloz shared the Nobel prize for this discovery revolutionising our understanding of solar system formation.

In 2016 it was discovered that Proxima Centauri, the star closest to us, has at least one planet not much larger than Earth tugging at the star. With such a small planet, the effect on the star's orbit is tiny—a change in velocity of only $1.4\,\mathrm{m\,s^{-1}}$. The instrumentation used by astronomers is precise enough to identify such small changes in velocity.

Astronomers' instruments continue to improve and can now detect the gravitational tug of much smaller planets. Improvements in telescope technology such as James Webb and the Transiting Exoplanet Survey Satellite (TESS), make discovering exoplanets significantly easier. Instruments at the observatory at Mt Kent in southern Queensland will be able to detect even smaller gravitational wobbles in distant stars, changes as small as $1\,\mathrm{m\,s^{-1}}$.

Queensland astronomer Jonti Horner (Figure 12.1.1) has discovered many exoplanets using gravitational wobble and other planet-hunting methods. But he is still impressed by the science behind these discoveries: "Stars are trillions or quadrillions of kilometres away. Proxima Centauri, the nearest, is more than 40 trillion kilometres distant. I find it astonishing we can measure something that is so distant and see a wobble that is comparable to the speed at which you or I would walk around the shops!"

FIGURE 12.1.1 Queensland astronomer Jonti Horner uses the gravitational pull on host stars to identify distant exoplanets.

KEY QUESTIONS

Forming and finding

1. Identify the key features of 'hot Jupiters' and why this makes them easier for astronomers to detect.
2. Use a scientifically credible source to detail an alternative to the 'wobble' method. Reference the source appropriately at the end of your description.

Analysing

3. Explain why technological advancements in measurement accuracy in astronomy were necessary for the discovery of Earth-sized exoplanets.
4. Astronomers can discover planets orbiting distant stars by observing the exoplanet's gravitational pull on its host star. The exoplanet Hypatia has a mass of 1.68×10^{28} kg (almost 10 times the mass of Jupiter).
   - **a** Calculate the magnitude of the gravitational force that the planet exerts on its host star, given that Hypatia orbits at an average distance of 195 000 000 km and the mass of its host star is 3.62×10^{30} kg.
   - **b** Determine the magnitude of the resulting acceleration of the planet's host star.

Gravitational waves and the Australian connection

The successful detection of gravitational waves in 2015 was the culmination of a century of physics. When Albert Einstein predicted such waves in his 1915 theory of general relativity, he said they could never be detected, as the displacement would be too small to measure.

According to the theory of general relativity, objects with mass bend spacetime. Two massive objects, such as black holes, that had been orbiting each other, would cause ripples in spacetime if they collided. These ripples are gravitational waves.

By 2015, the instruments at the Laser Interferometer Gravitational-Wave Observatory (LIGO) were accurate enough to measure displacements as small as one-thousandth the width of a proton.

LIGO is made up of two large facilities: one in Washington state, in the northwest of the USA (Figure 12.2.1a), and the other 3000 km southeast near New Orleans, Louisiana. Each facility comprises two 2 km long buildings at right angles, along which a laser is shone and reflected back. The two perpendicular beams should arrive simultaneously, with any tiny deviations indicating that the length of one building has increased or decreased.

And as a gravitational wave passes through Earth, that is precisely what happens. Depending on the source of the wave, one building or the other becomes about one quadrillionth of a mm (10^{-18} m) longer than the other for a few milliseconds as the wave passes.

Australian physicists played a key part in the project (Figure 12.2.1b), including working on the mirrors that position LIGO's lasers, the detectors that detect changes in path length, and software to interpret results. Australian gravitational waves research is coordinated by the ARC Centre of Excellence for Gravitational Waves Discovery (OzGrav).

a

b

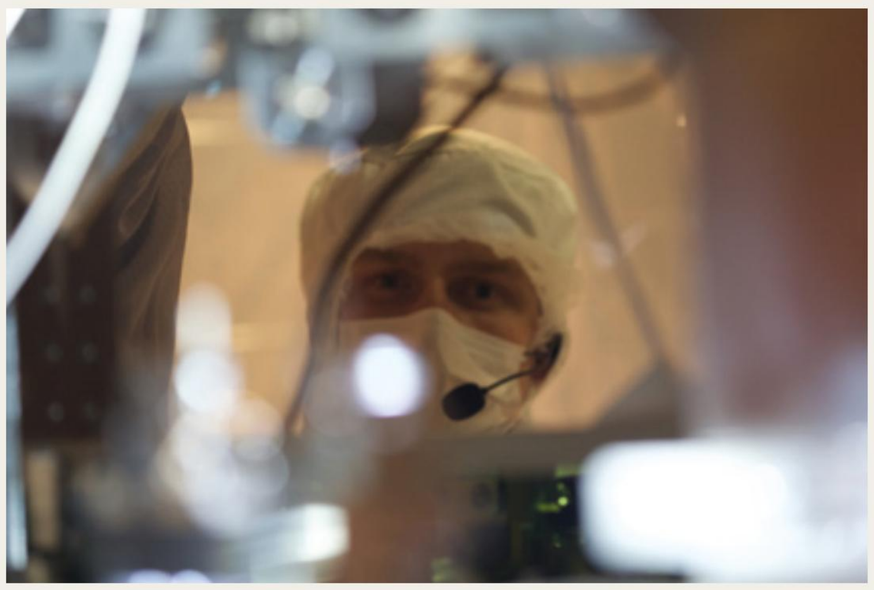

FIGURE 12.2.1 (a) LIGO's observatory in Washington state, USA, showing the two perpendicular arms of the facility. (b) Monash University (Australia) astrophysicist Chris Whittle in the optics vacuum chamber at LIGO, Washington USA, assisting with the replacement of an interferometer mirror. The cleanroom suit minimises dust, which can foul the equipment.

KEY QUESTIONS

Forming and finding

1. Describe how gravitational waves that pass through Earth influence the LIGO observatory.
2. In 2017 LIGO detected a gravitational wave of unknown origin (GW170817). Research how international collaboration was involved in discovering the source of these waves.
3. The 'I' in LIGO stands for Interferometer, which is a device which uses interference patterns to measure distances with extreme accuracy. Research and explain how the wave properties of light are utilised in interferometry. (HINT: You first learned about these properties in *Pearson Physics Queensland Units 1 & 2* Chapter 11, and they are also covered in Chapter 10 of this book.)

Analysing

4. Determine the dependent variable(s) measured by LIGO.
5. The first gravitational waves event to be measured, in September 2015, was the result of a collision between two orbiting black holes: one 36 times more massive than the Sun (7.16×10^{31} kg) and another 29 times more massive than the Sun (5.77×10^{31} kg). Because black holes are so dense, as they merged their centres were only 350 km apart. Calculate the gravitational force between the two black holes at this moment.

Artificial satellites and space junk

In October 1957, the first satellite, Sputnik I, was successfully placed into orbit. It lasted for three months before it ran out of power and burnt up in the atmosphere. This was the first time human beings had successfully launched an object into space and had it circle Earth.

Australia became the seventh country to launch a satellite into space when the Defence Department launched WRESAT from the Woomera test range in northern South Australia in 1967. The number of satellites launched into space has increased rapidly in recent years with networks of microsatellites such as Starlink. As of 2024 there are an estimated 10 000 satellites in orbit from over 70 states or organisations. This number has increased by at least 2000 satellites each year for the past three years. Figure 12.3.1 shows what they would look like if they were bright enough to all be seen around Earth.

Satellites fulfil several purposes from orbit, including:

- communications (television, radio, internet, telephone)
- climate and weather observations
- astronomy (Hubble Space Telescope, X-ray and gamma ray telescopes)
- military (spying, reconnaissance, 'killer' satellites)
- navigation (GPS, GLONASS, Galileo)
- Earth observing (remote sensing, mapping, biological surveys)
- habitation (space stations).

Satellites in low-Earth orbits of 160 km to 2000 km, typically have periods of between 90 minutes and 2 hours. Many spy and Earth-observing satellites are in this type of orbit, as are the International Space Station and the Hubble Space Telescope.

Satellites in medium-Earth orbits, from 2000 km to 35 786 km, include many navigation satellites such as GPS and remote-sensing satellites. These are located here as they can cover the surface of Earth at least twice in one day.

A special orbit of height 35 786 km above Earth's surface gives the satellite a period of 23 hours, 56 minutes and 4 seconds, which is the same as the period of Earth's rotation, hence the name geosynchronous orbits. A geosynchronous satellite will remain in the same position in the sky each day and are thus very useful for TV, radio and internet communications.

Higher orbits with periods longer than one day are generally used by the military, for weather monitoring and astronomical observations.

Objects with sufficient speed to attain orbit remain in orbit for a significant period of time. However, with defunct satellites and debris from satellite launches and space missions, the area around Earth is becoming increasingly crowded.

FIGURE 12.3.1 An artist's impression of the thousands of satellites currently orbiting Earth. About half of them are very close to Earth, only a few hundred kilometres above the ground, with the other half spread out in a ring approximately 36 000 km above the equator.

In addition to operational satellites, there are over 3000 satellites in orbit that have reached the end of their operational life or have malfunctioned. Military strikes on the satellites of other countries, as well as accidental collisions between satellites and space junk, further contribute to this debris.

The presence of this fast-moving space junk puts satellites and the International Space Station (ISS) at risk from collision. Currently about 25 000 pieces of space junk larger than 10 cm are being tracked and monitored. The estimated amount of space junk larger than 1 mm is more than 100 million pieces and 9 000 000 kg. There have been several occasions where satellites have been moved to avoid collisions with space junk. On one occasion, a piece of debris that is thought to have been a fleck of paint cracked a window of the ISS.

Even if concerted efforts are made to limit the lifetimes of satellites and to regulate the number of new satellites entering low-Earth orbits, the problem may well get worse by itself. Every time a substantial collision occurs, more debris is created. This, in turn, has the potential to cause further collisions, in a cascading effect.

The UN has passed a resolution to remove defunct satellites from low-Earth orbits by placing them in much higher orbits, or bringing them back to Earth and allowing them to burn up in the atmosphere.

KEY QUESTIONS

Forming and finding

1. Explain why 160 km is the lowest height limit above Earth's surface for low-Earth orbits.
2. Explain why geosynchronous orbits are the optimal orbit for communications satellites.
3. Research the methods used to protect satellites and space missions from space junk.

Analysing

4. Even though some of the debris is very small, its speed relative to another satellite may be up to 50 000 km h^{-1}. Calculate the kinetic energy of a 0.10 g fragment travelling at such a speed.
5. Figure 12.3.1 makes it look as if there is not much room left around Earth, particularly in low-Earth orbits (LEOs). To obtain an idea of how much room is available for satellites:
   - calculate the total volume of the low-Earth orbit range from an altitude of 100 km to an altitude of 2000 km
     - divide it by the approximate number of current satellites, 10 000
     - (HINT: Find the volume of a sphere, using $V = \frac{4}{3}\pi r^3$ and remember to include the radius of Earth, 6400 km).

Models of the universe

From ancient times, people have always sought ways to explain their world and their place in it. They would have looked at the sky above and decided that the heavens were under the control of various gods and spiritual identities beyond their comprehension. They observed that the Sun and Moon, together with many other bodies only visible at night, moved in predictable paths from east to west across the sky. It was this repetitive pattern which soon led to a model in which the motion of those bodies could be understood in concrete terms.

The earliest model was perhaps the most obvious one. The geocentric model (Figure 12.4.0) described the heavenly bodies as travelling around Earth in circular orbits centred on Earth (from the Greek geos for 'Earth'). Each body followed its own individual path against the backdrop of all the stars, which seemed not to move at all, but to be fixed on the celestial sphere—much like stars stuck on a bedroom ceiling. The Sun and Moon were closest to Earth, and the other members of the system—the wandering planets and comets—were at varying further distances. The immovable stars were the most distant of all.

FIGURE 12.4.1 Elaborate illustrations of the geocentric universe adorned many texts in the Middle Ages.

From years of observations, Ptolemy, a Greco-Roman philosopher in Alexandria in the 2nd century, formulated a mathematical description of the geocentric system. Ptolemy's model could be used to accurately predict the positions of the Moon and planets, as well as eclipses. As such, it can be described as an 'empirical' model: one that fits the observations and can be used to make predictions. To describe the retrograde motion of the planets, his model had to incorporate various complications such as 'epicycles'. (A planet will generally seem to move in a steady direction across the background of distant stars. However, some planets occasionally move for a short time in the opposite, or retrograde, direction). Although all orbits were perfect circles centred on Earth, the planets followed their own small orbits around centres that orbited Earth.

Ultimately, it was these complications that led to the demise of Ptolemy's geocentric model and the acceptance of the better, theoretical heliocentric or Sun-centred model. The heliocentric model had been proposed by Aristarchus (c. 310–230 BCE) but was not widely accepted because it seemed to contradict common sense.

It took some courage for Nicolaus Copernicus to publish his theory in 1543, as it contradicted the idea that Earth occupied the prime position in the universe, as implied by the Bible. While not abandoning circular orbits and epicycles altogether, Copernicus centred the planetary orbits on the Sun, and the Moon's orbit on Earth. He also:

- placed Mercury, Venus, Earth/Moon, Mars, Jupiter and Saturn in order from the Sun
- described Earth's day–night rotation, its annual solar revolution and Earth's tilted axis to explain the seasons
- showed that planetary retrograde motion was explained by Earth's motion around the Sun.

Although the Copernican model could better explain astronomical observations, it was still rather complicated and must be regarded as a stepping stone. The theories of Kepler and Newton detailed in Chapter 4, built upon these ideas as well as the modern theories which followed, such as the acceleration of the expansion of the universe evidenced by Australian Nobel prize winner, Brian Schmidt.

KEY QUESTIONS

Forming and finding

1. Contrast the key feature of heliocentric and geocentric models.
2. The article claims the expansion of the universe is accelerating. Use this claim to formulate a research question.
3. The theories detailed in the article predominantly focus on the solar system. Locate a scientifically credible source which details when humans first became aware of systems beyond Earth's, confirming the need to refine the model of the universe.

Analysing

4. What discovery lead to the eventual abandonment of the Geocentric model? With reference to the laws of motion, explain why this was necessary.
5. Explain the role of time in the collection of data required to verify a proposed model claiming to predict the motion of planets.

Solar storms

The Sun is formed of a type of fluid called plasma, which is a hot mixture primarily comprised of ionised hydrogen. Coronal circulation causes this plasma to flow around the Sun, creating a system called a solar dynamo. The movement of charged hydrogen forms an electric current generating a magnetic field. This changing magnetic field influences the plasma's motion via electromagnetic induction, creating a feedback loop. This sustains the Sun's magnetic field—the heliosphere—protecting the solar system from dangerous galactic cosmic radiation the same way Earth's magnetic field protects from the Sun's radiation.

This protection comes at a cost to modern infrastructure. The flow of plasma around the Sun is complex, creating tangled loops in its magnetic field. When these loops cross, a magnetic reconnection occurs. This involves a reshaping of the magnetic field and causes the ejection of huge quantities of radiation and plasma from the Sun. These events are referred to as solar flares and coronal mass ejections (CMEs), respectively.

Solar flares emit radiation across the electromagnetic spectrum in all directions. The radiation pressure from these emissions carry charged particles of solar wind toward Earth. Earth's atmosphere absorbs the radiation and Earth's magnetic field deflects the charged particles, except for small amounts which enter at weak points of the field around the poles, creating aurora.

CMEs involve the ejection of billions of tonnes of plasma from the Sun. Unlike the radiation from solar flares, CMEs are directional. If Earth happens to be in their path, these plasma ejections create geomagnetic storms which can induce electrical currents, damaging electrical infrastructure. The charged plasma compresses and heats Earth's magnetic field. This increases drag on satellites causing them to slow and lose altitude. For example, the Aurora Australis storms in May 2024 required more than half of all active satellites to manoeuvre to compensate for the effects of the storm. Figure 12.5.1 shows a CME from 31 August 2012. Fortunately, this CME did not collide with Earth, but passed close enough to cause Aurora.

FIGURE 12.5.1 An image of the 31 August 2012 CME taken by NASA using an observatory in the extreme ultraviolet range. Earth is not this close to the Sun and has been included only for scale purposes.

In 1859, the Carrington Event, the largest recorded solar event induced enough current in global telegraph systems to set them on fire (including in Australia). More recently, in 1989, a solar event plunged Quebec into darkness for nine hours by damaging key transformers in Quebec's power grid. In 1972, solar activity triggered the explosion of naval sea mines off Vietnam's coast, which explode when they detect magnetic disturbances caused by the metal hulls of nearby vessels.

The risk is higher today. A severe solar event could induce currents strong enough to destroy transformers, deactivating power grids and disabling fuel and water pumps. Storms could damage semiconductors in digital devices, erasing computer memory (by magnetically flipping 1s into 0s in digital storage), disabling the stock exchange and wiping bank accounts, and crippling the internet due to induced currents destroying undersea cables. The potential economic damage could run into trillions of dollars, with complete recovery taking years.

Fortunately, modern monitoring systems provide advance warnings of solar events. Satellites like NASA's Advanced Composition Explorer (ACE) track space weather and alert Earth to solar events, allowing time to shut down power grids and satellites, minimising damage. Additional monitoring capabilities are on the horizon, with two

satellites—the Space Weather Follow-On – Lagrange 1 (SWFO-L1) and the Interstellar Mapping and Acceleration Probe (IMAP)—scheduled for launch in 2025.

In Australia the National Emergency Management Agency (NEMA) conducted a national crisis training exercise in 2024 called 'Exercise Aurora' to test and refine Australia's preparedness for solar events. Exercises like these lead to increased preparedness, an understanding of mitigation strategies, and technological innovation, such as developing transformers with increased tolerance for solar activity.

KEY QUESTIONS

Forming and finding

1. Contrast solar flares and CMEs.
2. Identify the physical laws involved in the feedback loop caused by coronal circulation.
3. The article refers to solar wind. Locate a scientifically credible source which explains solar wind. Summarise the explanation from the source and include a reference using appropriate referencing conventions.

Analysing

4. The article claims that CMEs can damage transformers in the electricity grid. Develop a research question from this claim.
5. Identify at least two limitations which would need to be considered when implementing a protection strategy against solar activity.

Superconductivity

Superconductors are materials that have no resistance to the flow of electric current. Materials that act as superconductors open a world of exciting applications in physics. The history of the discovery of superconductors has its beginnings in the early 1900s in the Netherlands, but the theories of producing and utilising these materials are constantly being revised and restructured.

Technological breakthroughs have often led to advances in physics. This was the case in 1908 when Kamerlingh Onnes, at the University of Leiden in the Netherlands, succeeded in liquefying helium. Helium liquefies at 4.2 K (–268.9°C). It was known that the electrical resistance of metals decreases as they cool, so one of the first things that Onnes and his assistant did was to measure the resistance of some metals at these very low temperatures.

Onnes was hoping to find that as the temperature of mercury dropped towards absolute zero its resistance would also gradually drop towards zero. What they found, however, was a complete surprise. At 4.2 K its resistance vanished completely!

Onnes coined the word 'superconductivity' to describe this phenomenon. Soon he found that some other metals also became superconducting at extremely low temperatures: lead at 7.2 K and tin at 3.7 K, for example. Curiously, metals such as copper and gold, which are very good conductors at normal temperatures, do not become superconducting at all. Onnes was awarded the 1913 Nobel Prize in Physics for his work in low-temperature physics.

Unfortunately, the superconducting metals lost their superconductivity in magnetic fields of about 0.1 T, which is quite a moderate field. However, in the 1940s it was found that some alloys of elements such as niobium had higher 'critical temperatures' and, more particularly, retained their properties in stronger magnetic fields. By 1973 the niobium–germanium alloy Nb_3Ge held the record with a critical temperature of 23.2 K in a magnetic field of 38 T, an extremely strong field.

In 1986 an entirely new and exciting class of superconductors was discovered. Georg Bednorz and Karl Müller, working in Switzerland, found that compounds of some rare earth elements and copper oxide had considerably higher critical temperatures. They received the 1987 Nobel Prize in Physics for their work.

These new high-temperature superconductors are ceramic materials made by powdering and baking the metal compounds. Most ceramics are insulators; it was a combination of good science and inspired guesswork that led Müller to try such unlikely candidates for superconductivity. So far, the record is held by Lanthanum decahydride (LaH_{10}) under very high pressure with a critical temperature, T_c of about 250 K—still rather cold, but significantly above the temperature of readily available liquid nitrogen (77 K). The abundance of nitrogen gas in the atmosphere (78%) makes liquid nitrogen a much cheaper alternative than liquid helium to use to cool superconducting materials. In the years since the discovery

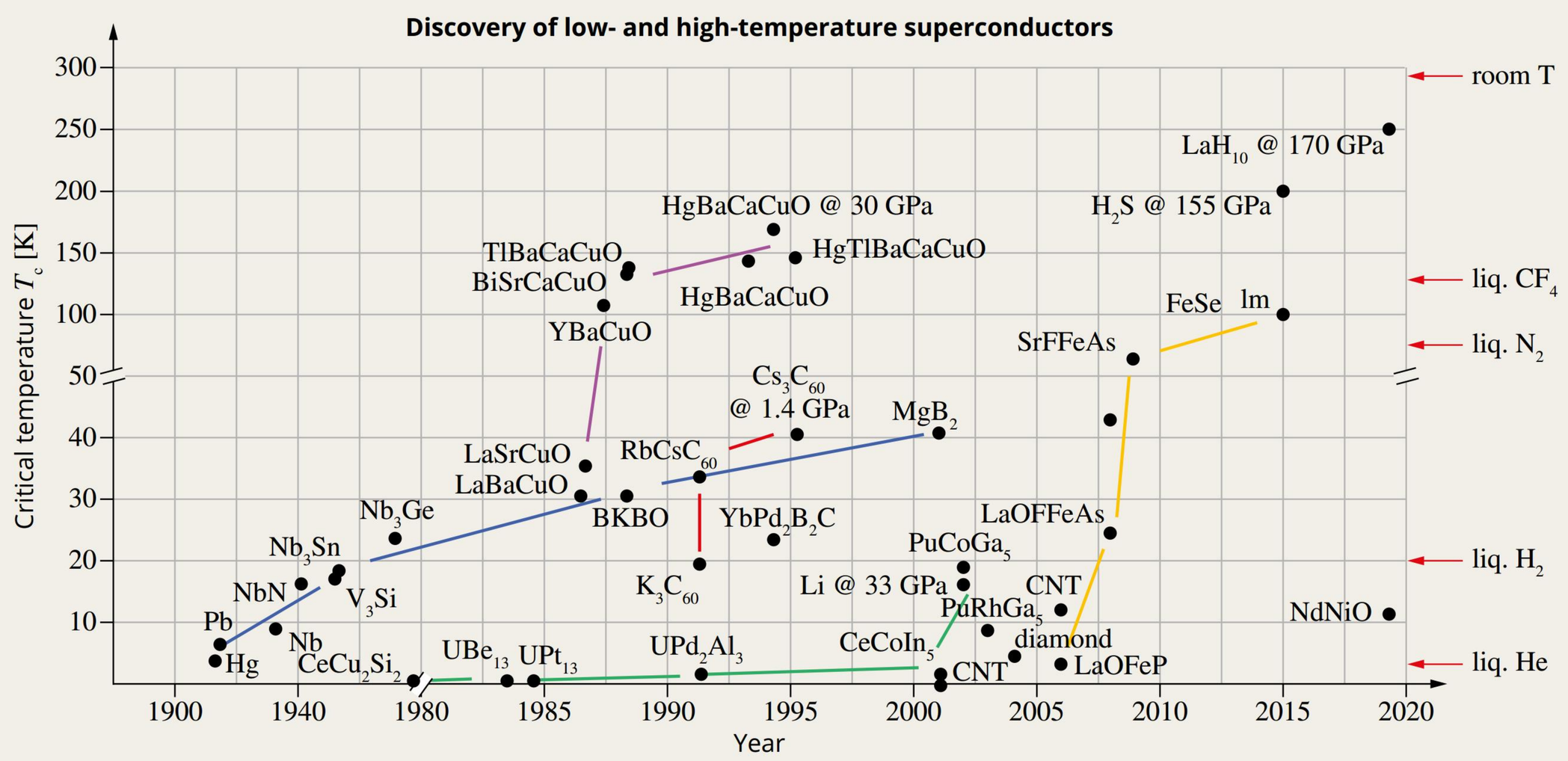

FIGURE 12.6.1 Since its beginnings in the early 1900s, enormous advances have been made in the increase of the critical temperature of superconducting materials.

of high temperature conductors, there have been many breakthroughs in the discovery of both low- and high-temperature superconductors (Figure 12.6.1).

Superconductivity, particularly in the newer materials, is still not fully understood. It can only be discussed in terms of quantum physics, but one picturesque way of thinking about it is that electrons pair up and 'surf' electrical waves set up by each other in the crystal lattice of the material.

Much of the great potential of superconductivity lies in the magnetic properties of superconductors. If an eddy current was produced in a conductor with very little or no resistance, the eddy current would not die away. If a magnet is brought near a superconductor, the induced current will create a flux within the superconductor that opposes the field of the magnet and repels the magnet. This results in magnetic levitation (Figure 12.6.2), a phenomenon known as the Meissner effect.

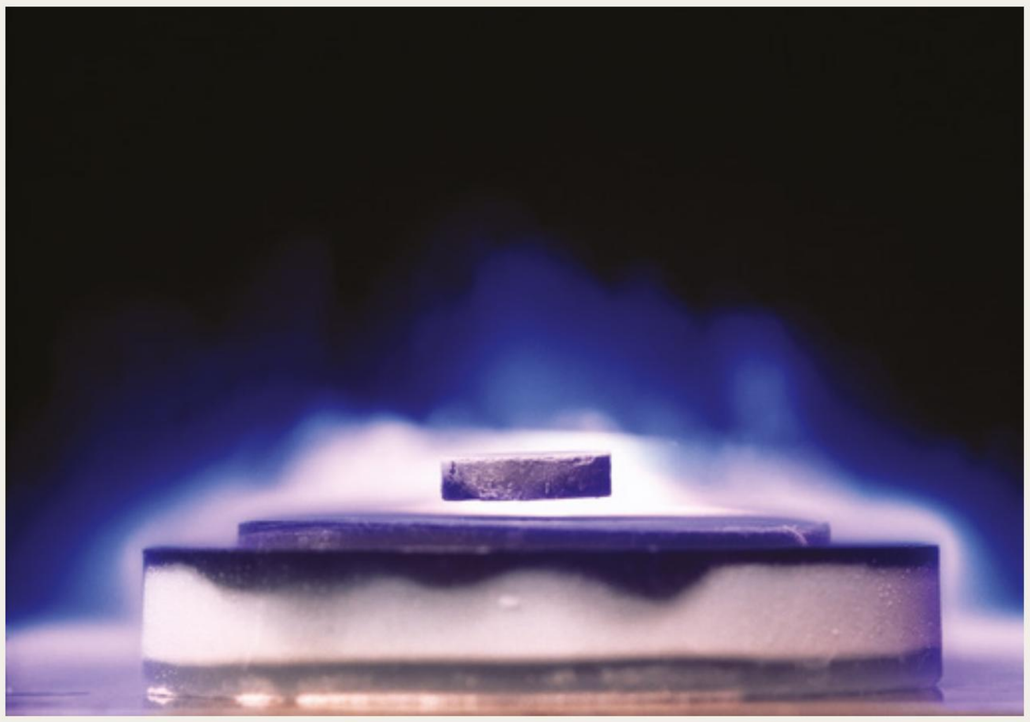

FIGURE 12.6.2 A disc magnet is repelled by a superconductor because the magnet induces a permanent current in the superconductor, which results in an opposing field.

The possibilities of superconductivity are enormous: low-friction transport, no-loss transmission of electricity, and smaller, more powerful electric motors and generators. Superconducting magnets might also be used to contain the extremely hot plasma needed for hydrogen fusion, producing nearly pollution-free energy in much the same way as the Sun. However, many challenges must be overcome before these advancements can be fully realised.

KEY QUESTIONS

Forming and finding

1 a Describe one of the first experiments that Kamerlingh Onnes and his assistant completed after they had successfully liquefied helium.
   b In your own words, explain what claim the experiment intended to investigate.

2 Describe the Meissner effect and how this effect is useful.

3 Despite the advances in superconductor technology, these materials have not yet replaced electric circuits commonly in use today. Furthermore, there are many theories and heated debates about how superconductivity works. Conduct some research to outline what cuprates and pnictides are, and compare the way they achieve superconductivity.

Analysing

4 LK-99 is claimed to be a room-temperature superconductor. Research LK-99 and then comment on how experimental replication enhances the validity of a research claim.

5 What implications do the findings of Kamerlingh Onnes lab's experiments have for future research or practical applications in the field?

The dual characteristics of light

The nature of light has been investigated and debated for centuries, with each generation of scientists building on the work of the last. In the 20th century, scientists came to the realisation that light behaves both as a wave and as a particle.

Christiaan Huygens published his wave theory of light in 1690. It was the first mathematical description of light. Huygens' theory explained geometrical optics in terms of wavefronts and rays, and the propagation of light by means of spherical waves produced along the wavefront. Huygens had quite an interest in lenses, and ground the lenses he used in experiments himself. Huygens based his ideas on experiments involving refraction. Wave theory could explain why light that is shone through a pinhole or slit would spread out rather than travelling in a straight line. Initially, Huygens' wave theory was based on light being a longitudinal wave that cannot undergo polarisation. But without polarisation it was not possible to explain the recently (for Huygens) discovered birefringence that had been observed in such materials as Icelandic spar (calcite). Because it was not able to explain birefringence, Huygens' theory was not widely accepted in the scientific community of the time. This was resolved much later when it was realised that light was a transverse wave, as birefringence is a polarisation effect.

Opposing Huygens' wave theory of light, Sir Isaac Newton proposed a corpuscular theory of light in his 1704 book *Optiks*. Newton considered that light is made of small discrete particles known as corpuscles which travel in a straight line in rays with a finite velocity. Newton argued that because waves don't tend to travel in straight lines, the only way to explain reflection and refraction is if light is composed of particles. The key demonstration of this was passing white light through a pair of prisms set up so that the light produced a spectrum after the first prism and reformed the beam of white light with the second prism (Figure 12.7.1). Mostly due to Newton's reputation, the corpuscular theory of light was predominant until Thomas Young performed his double-slit experiments in 1801, the results of which could not be explained by the corpuscular theory of light.

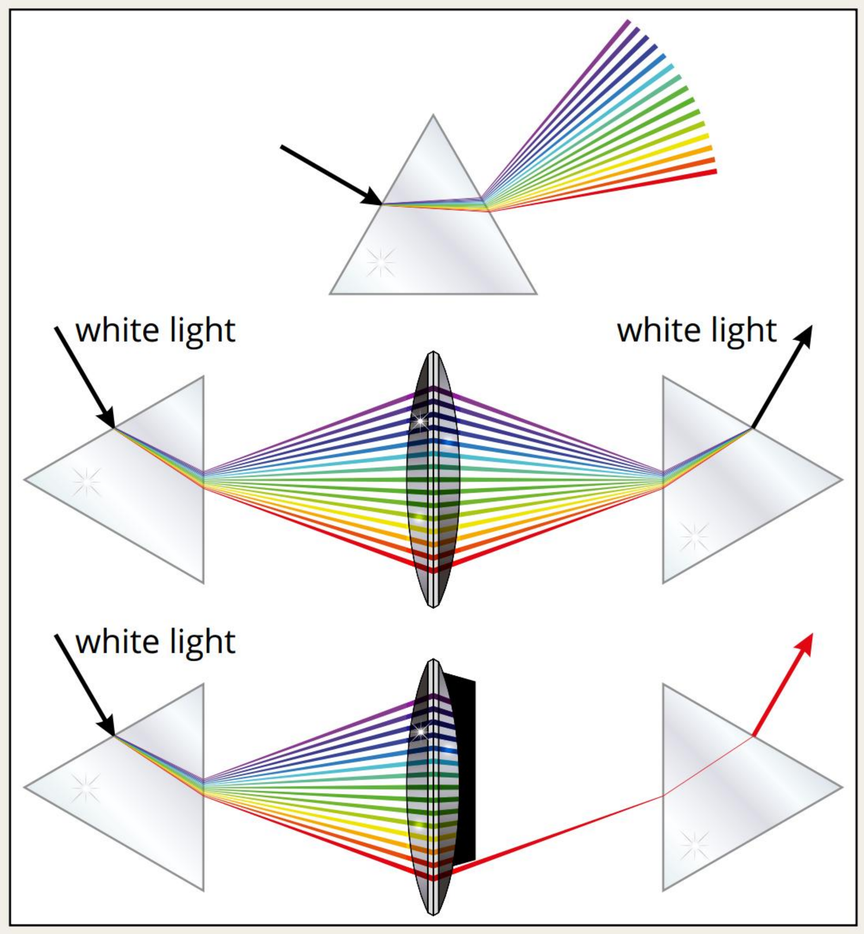

FIGURE 12.7.1 A diagram showing Newton's observations. The first prism breaks the white light into a spectrum and the second prism combines the spectrum back into white light. By blocking most of the spectrum between the two prisms, a single colour can be selected.

Beginning in the early 1800s, the dominant theory in the scientific community was that light consisted of waves. The double-slit experiments, conducted by Thomas Young, had shown that light travelling through two slits produced an interference pattern. If light was a particle, no interference pattern would be observed.

In 1900 Max Planck solved the black-body problem with the notion of quantised energy. His calculations revealed the quantisation of light, which seemed to indicate that light is a particle. Planck (and other scientists) viewed this at the time as a problem with his approximations rather than reality.

However, Einstein built on Planck's work, using it as the basis for his explanation of the photoelectric effect. His explanation, published in 1905, required that light travels as particles (later called photons). Although Einstein later won the Nobel prize for that work, his explanation was not widely accepted by the physics community.

Scientists were still expecting a wave-based explanation of the photoelectric effect to emerge at some time. The turning point for the particle view of light came in 1923 when Arthur Compton, looking for direct evidence of the particle nature of light, performed experiments in which he aimed X-rays and gamma rays at electrons. Compton showed that the rays emerged from the collisions just as particles would. Thus, light had momentum and must be a particle.

At about the same time, theorist Louis de Broglie was arriving at his discoveries. de Broglie started with Einstein's ideas about light being a particle and combined this with Einstein's special relativity, which established the equivalence of mass and energy. de Broglie argued that light, being electromagnetic radiation, has energy, and if energy is equivalent to mass, then perhaps light could exhibit the same properties as particles. The leap that de Broglie made in 1923 was that if light (a wave) can behave like a mass (particles), then why couldn't particles behave like a wave?

Erwin Schrödinger in 1926 built on de Broglie's work to explain the properties of electrons in atoms behaving as waves. Werner Heisenberg had already done similar work, but in his mathematical description, electrons were particles. There was also experimental evidence that electrons showed both wave and particle behaviour.

With mounting evidence on both sides of the wave–particle debate, Bohr, in 1927, developed his complementarity principle: some mutually exclusive views of nature could both be true, just not at the same time. The wave–particle duality of both photons and matter was his key example. For any given phenomenon, light can behave as a particle or as a wave, but never both.

Bohr used a thought experiment based on the double-slit experiment to illustrate this (Figure 12.7.2). A beam of light is fired at a double slit. If the light behaved as a particle the photons would pass through individual slits and produce two fringes on the backing screen. If the light behaved as a wave, an interference pattern would be observed on the backing screen. But if only one photon at a time is directed through the double-slits, would it behave as a particle and produce a single fringe or would it behave as a wave forming an interference pattern on the backing screen? Based on the concept of wave–particle duality, Bohr believed interference could still occur with individual photons acting as waves.

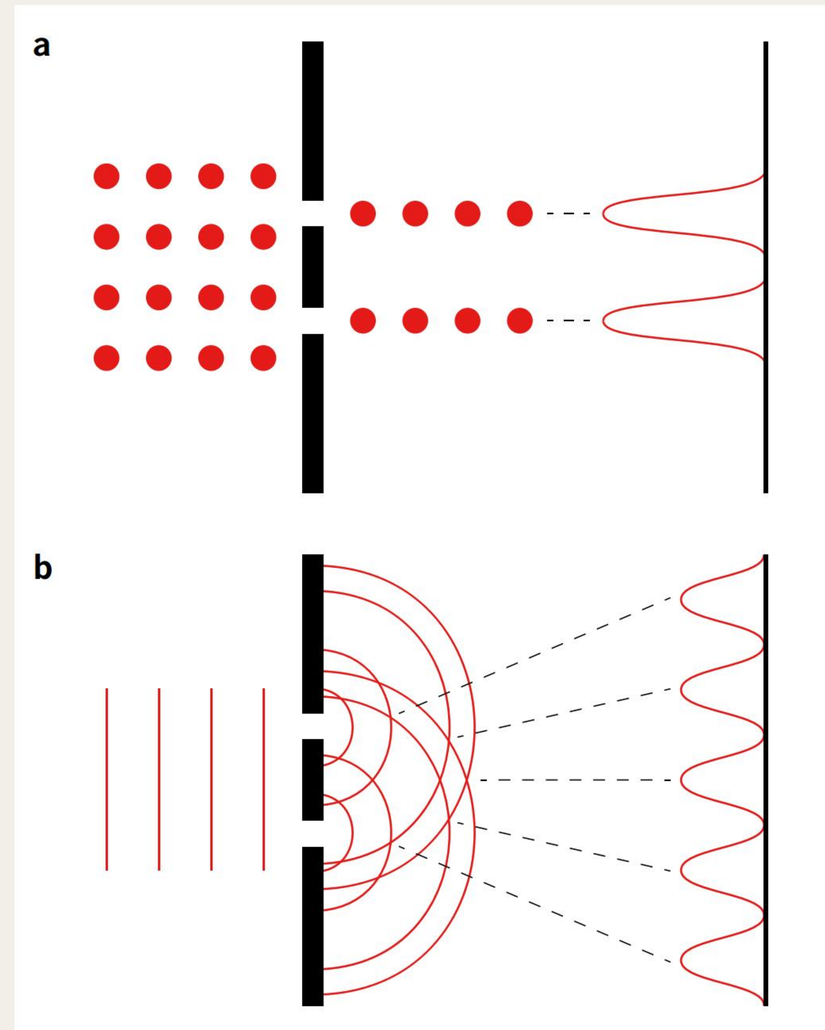

FIGURE 12.7.2 When light behaves as particles, shining it through a double slit results in two distinct lines (a). However, if light behaves as a wave an interference pattern is formed (b).

This was a thought experiment in Bohr's day, but real experiments of this description have since confirmed that Bohr was indeed correct. Bohr's complementarity principle is now known as the Copenhagen interpretation of quantum mechanics, named after Bohr's home city.

KEY QUESTIONS

Forming and finding

1. Recall why Newton rejected the idea of light behaving as a wave.
2. Create a timeline of the major developments in the investigation of the nature of light. Use the information above and conduct some further research.
3. The article claims that real single-particle double-slit experiments have been performed, confirming Bohr's complimentary principle. Locate a source detailing one of these experiments and provide a reference using appropriate referencing conventions.

Analysing

4. Identify the examples of experimental evidence detailed in the article.
5. Another example of experimental evidence used in this debate was the Michelson–Morley Experiment (*Pearson Physics Queensland Units 1 & 2,* pages 516 – 517). Summarise the alternate theory the Michelson–Morley experiment was performed to investigate and what the experimental evidence indicated.

The Large Hadron Collider and the Higgs boson

There are properties of particles that were not explained by the original Standard Model. The W and Z bosons discussed in Chapter 11.3 have relatively large masses of around 80 and 90 GeV, about 100 times larger than a proton, which has a mass of around 938 MeV. However another boson, the photon, is massless. Why is this the case? Why do some particles have mass and others do not?

The mass of particles cannot be predicted from the Standard Model you have learnt about so far; a new explanation is needed. This is where the Higgs field and the Higgs boson come in. When a particle passes through the Higgs field and interacts with it, it gets mass. The more strongly it interacts with the Higgs field, the more mass the particle has. You will already be familiar with the idea that fields are all around us, and that they can't be observed directly. This is the case with the Higgs field, but the Higgs field has a Higgs boson associated with it, which was predicted by Peter Higgs and his colleagues, and which could potentially be found. However, to search for it, a new type of particle collider was needed.

The Large Hadron Collider (LHC), at CERN on the border of France and Switzerland, was created to answer questions physicists still had about the Standard Model, in particular to test the prediction of the existence of the Higgs boson.

The LHC is the largest scientific instrument ever built: the tunnel has a circumference of 27 km with an average depth of 100 m below ground level (Figure 12.8.1). It is located underground for cost reasons, but this also has the extra benefit of shielding the accelerator from external radiation. Due to its groundbreaking work and enormous size, the LHC is probably the best-known particle accelerator outside of particle physics research. However, it is only the most recent and highest-energy accelerator in a series of accelerators and experiments at CERN. Together, the particle detectors working with the LHC allow specialised investigations at the leading edge of particle-physics research.

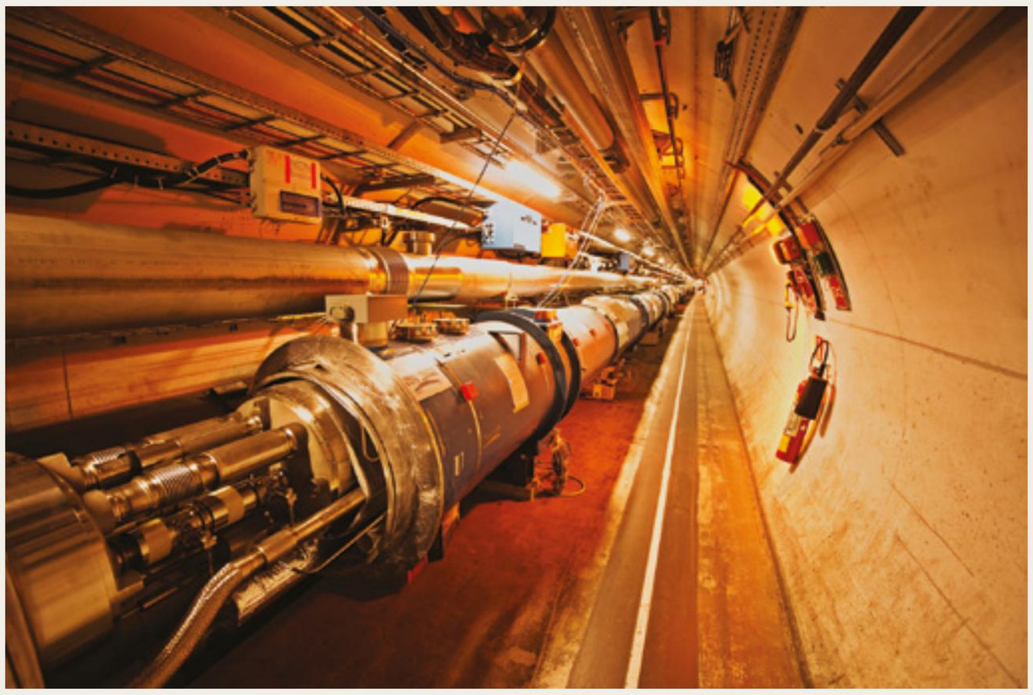

FIGURE 12.8.1 A section of the LHC's 27 km tunnel

In 2012, the discovery of a candidate for the Higgs particle was announced; a particle had been found with a mass of 126 GeV, which was consistent with theoretical predictions (Figure 12.8.2). On 10 December 2013, two of the original researchers, Peter Higgs and François Englert, were awarded the Nobel Prize in Physics for their work and prediction. The successful detection of the Higgs boson and subsequent determination of its mass was a major achievement of the LHC. However, physicists are not sure whether this is just an addition to the Standard Model, or if it suggests a new model of particle physics is needed.

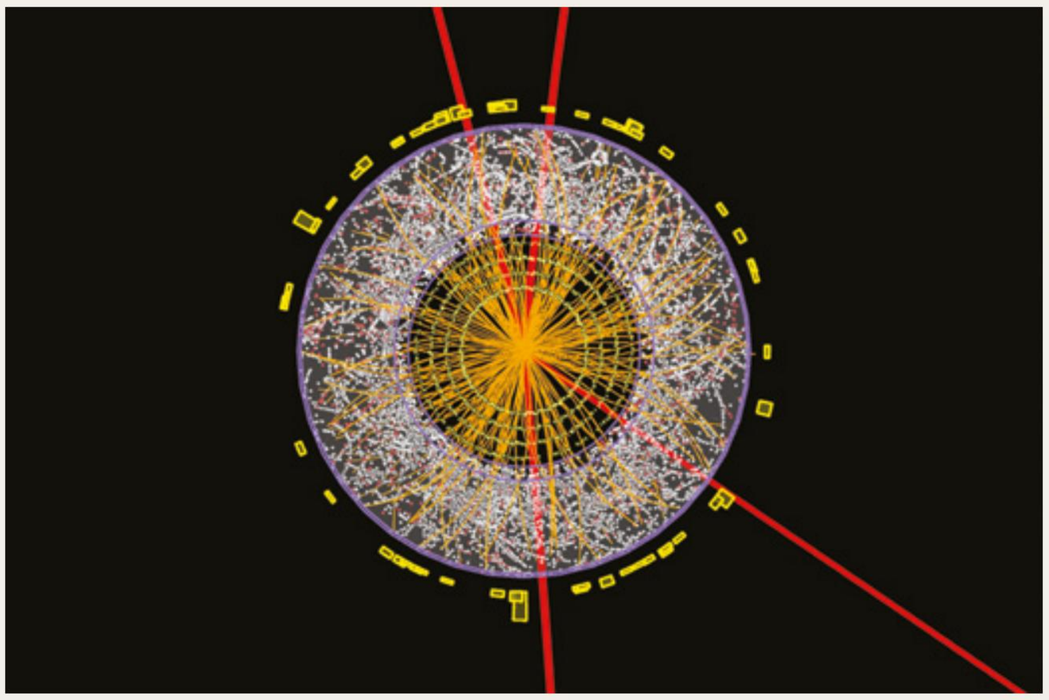

FIGURE 12.8.2 The image shows tracks of particles and measurements of their energies in the ATLAS detector at the LHC. The nature and energies of the particles produced are consistent with predictions of the formation of a Higgs boson.

Other goals of the LHC

The Standard Model is extremely successful in predicting the existence of particles and their behaviour. However, it is unable to answer questions about dark matter, and why there is comparatively very little antimatter in the universe, among others. The main goal of the LHC is to add to the understanding of particle physics beyond the Standard Model.

Some examples of other work being undertaken at the LHC, apart from the search for the Higgs boson, are listed below.

- Gauge bosons—the force-carrying particles studied in Chapter 11—are used to explain forces being exerted on particles by fields. Scientists are seeking a unified theory for the four natural forces. The Standard Model links the weak nuclear force, the strong nuclear force and the electromagnetic force, but is unable to construct a similar theory for gravity.
- Supersymmetry—the existence of more massive particles than are currently known—could lead to a unified theory.
- Astronomical observations suggest that only 4% of all the matter in the universe is visible. The LHC is searching for evidence of dark matter and dark energy, which are theorised to account for 23% and 73% of the remaining matter respectively.
- Matter and antimatter existed together in equal quantities at the time of the Big Bang but today, as far as scientists know, there is comparatively very little antimatter. Experiments at the LHC will attempt to determine why.
- Heavy ions, such as lead, colliding at high energies form hot, dense matter. The LHC will be used to investigate the state of matter called the quark–gluon plasma, which is theorised to have existed in the early universe.

KEY QUESTIONS

Forming and finding

1 The Standard Model does not explain several phenomena of the universe. State two areas of work that the LHC is undertaking to explain these phenomena.

2 Describe how the Higgs boson explains how particles get their mass.

3 List two limitations in the Standard Model which research at the LHC is being conducted to address.

Analysing

4 Comment on whether the Higgs boson was found through experiment, theory or both.

5 How did the findings from the LHC contribute to validating the theoretical predictions about the Higgs boson's mass?

The Hafele–Keating experiment

Shortly after Einstein first discussed time dilation in 1905 a debate emerged, referred to as the clock problem. This occurred due to the implications relativity had for the timekeeping of moving clocks compared to stationary clocks. A popular version of the clock problem is the twin paradox (discussed at length in Chapter 8), made popular by the physicist Paul Langevin in 1911.

This debate would die down and re-emerge constantly. In the early 70s its re-emergence prompted the physicists Joseph Hafele and Richard Keating to experimentally verify the effect. Seemingly, they grew tired of the continual written debates and wanted a solution. Their paper opens with the following sentence:

'In science, relevant experimental facts supersede theoretical arguments.'

The experiment itself was straightforward (Hafele and Keating describe it as '*simple and direct*'). Four atomic clocks (Figure 12.9.1) were flown on a regular commercial aircraft flight (tickets were purchased under the name 'Mr Clock'). They first flew eastward, and then westward. These four clocks were then compared with a control clock kept at the U.S. Naval Observatory.

FIGURE 12.9.1 A Caesium atomic clock similar to the one used by Hafele and Keating. These clocks use the known frequency of an atomic transition of caesium (9 192 631 770 per second) to record time.

The results are remarkably close to the predicted values, especially given the simplicity of the experiment, as shown in Table 12.9.1.

TABLE 12.9.1 Results of the Hafele–Keating experiment

	$\Delta t(ns)$	
	Eastward flight	**Westward flight**
Predicted difference ± estimated error	–40 ± 23	275 ± 21
Mean measured difference ± standard deviation	–59 ± 10	273 ± 7

It is important to understand why the both directions were investigated in this experiment. Since Earth rotates, the control clock on the ground is not in an inertial reference frame. To account for this, the frame of reference used in the experiment was stationary with respect to Earth's centre. As a result, the clock moving eastward had the highest velocity (hence losing the most time), followed by the clock on the ground, which moves through the reference frame at the speed of Earth's rotational speed. The westward flight, had the lowest velocity since it was flying against Earth's rotation.

This experiment verified the effect of relativity and ended the clock problem debate. It has since been verified repeatedly by ground-based experiments, as well as using atomic clocks on board satellites to compare with ground values. Perhaps the most interesting example is NASA's twin study (Figure 12.9.2). From 2015 to 2016 two identical twin astronauts were involved in a multidimensional analysis to investigate the impact of spending time in space. Astronaut Scott Kelly spent one year aboard the international space station while his identical twin, astronaut Mark Kelly, remained on Earth. This allowed NASA to compare multiple variables between the two twins. Over the course of the year, this resulted in Scott experiencing approximately 8 milliseconds less time than Mark.

FIGURE 12.9.2 Identical twin astronauts Scott and Mark Kelly

KEY QUESTIONS

Forming and finding

1. In your own words, explain the claim the Hafele–Keating experiment aimed to investigate.
2. Explain how reference frames were considered in the Hafele–Keating experiment.
3. The article states this experiment has been verified through replication. Find a scientifically credible source which details one of these replications.

Analysing

4. What methods were employed to ensure the accuracy and reliability of the data analysis process?
5. What implications do the findings of the Hafele–Keating experiment have for practical applications in GPS technology?

Noether's theorem

Amalie 'Emmy' Noether (Figure 12.10.1) was one of the leading mathematicians of her time and arguably the most important mathematician in the fields of abstract algebra and modern theoretical physics. These contributions were made despite commencing her studies during a period where women were banned from studying or working at university; her work as a professor and lecturer was unpaid. Noether also had to flee to America when the Nazi government fired Jews from all university positions ahead of the Holocaust.

FIGURE 12.10.1 Mathematician Amalie 'Emmy' Noether

Noether's story begins with relativity. Special relativity represented a significant step in the direction of modern physics from classical mechanics. Despite this breakthrough, the theory contained limitations. It was unable to account for the behaviour of accelerating objects, for instance, which Einstein described as 'preferencing Inertia'. He saw no reason for why the universe should exhibit a preference for any particular state of motion.

Einstein began working on a theory of general relativity, capable of explaining all states of motion, not only the special case of constant motion in special relativity. This involved work on gravitational field equations from a physics perspective.

Around the same time, mathematician David Hilbert was working on a unified theory of gravity and electromagnetism. This involved work on gravitational field equations from a mathematical perspective.

In 1915, the collegiality between Hilbert and Einstein soured, with both publishing papers on field equations within days of each other. This led to some controversy over who was first to publish the work. It is now agreed by most historians that Einstein was first conceptually, with contributions from Einstein, Hilbert, and Noether on the mathematical side.

Hilbert was struggling to reconcile what appeared to be violations of energy conservation in general relativity. Recognising her mathematical brilliance, he invited Noether to help solve this problem. Noether achieved far more than this by investigating Einstein and Hilbert's work; she discovered the connection between conservation laws and symmetries, called Noethers theorem, which revolutionised modern physics.

As explained in Chapter 11.4, in physics, a symmetry of a physical system is any transformation that leaves a system and the laws of physics explaining the system unchanged. What Noether mathematically proved was remarkable: every symmetry corresponds to a conservation law, and vice-versa. For example:

- space-translation symmetry—if the laws of physics work the same no matter where you are in space, momentum is conserved
- time-translation symmetry—if the laws work the same no matter when you do an experiment, energy is conserved
- rotational symmetry—if the laws work the same when you rotate something, angular momentum is conserved.

Noether's theorem offers a profound insight into the nature of physics. Conservation laws are fundamental to all known laws of physics. For example, in the standard model, conservation laws describe how particle scattering processes work in particle accelerators such as the Large Hadron Collider, and how particles and fields interact at small scales and high energies (quantum field theory). Noether's theorem is really a part of every aspect of modern physics because the theorem provides a structured process through which new theoretical physics is developed.

KEY QUESTIONS

Forming and finding

1. Distinguish between special and general relativity.
2. Select one of the three symmetries detailed in the article and provide an example of a scenario which demonstrates this type of symmetry.
3. Identify a form of symmetry which is not detailed in the article 'there are many others' from a scientifically credible source. Cite this source using appropriate referencing conventions.

Analysing

4. Describe a limitation present in special relativity which lead to the development of general relativity.
5. What implications does Noether's theorem have for future research?

APPENDIX A: Symbols, units and fundamental constants

TABLE 1 The 24 SI prefixes, their symbols and values

Prefix	Symbol	Multiplier	Prefix	Symbol	Multiplier
deca	da	10^{1}	deci	d	10^{-1}
hecto	h	10^{2}	centi	c	10^{-2}
kilo	k	10^{3}	milli	m	10^{-3}
mega	M	10^{6}	micro	µ	10^{-6}
giga	G	10^{9}	nano	n	10^{-9}
tera	T	10^{12}	pico	p	10^{-12}
peta	P	10^{15}	femto	f	10^{-15}
exa	E	10^{18}	atto	a	10^{-18}
zetta	Z	10^{21}	zepto	z	10^{-21}
yotta	Y	10^{24}	yocto	y	10^{-24}
ronna	R	10^{27}	ronto	r	10^{-27}
quetta	Q	10^{30}	quecto	q	10^{-30}

TABLE 2 Some physical constants

Description	Symbol	Value
Unit 1: Thermal, nuclear and electrical physics		
specific heat capacity of ice	c_i	$2.05 \times 10^{3}\,\mathrm{J\,kg^{-1}\,K^{-1}}$
specific heat capacity of water	c_w	$4.18 \times 10^{3}\,\mathrm{J\,kg^{-1}\,K^{-1}}$
specific heat capacity of steam	c_s	$2.00 \times 10^{3}\,\mathrm{J\,kg^{-1}\,K^{-1}}$
latent heat of fusion of water	L_{fusion}	$3.34 \times 10^{5}\,\mathrm{J\,kg^{-1}}$
latent heat of vaporisation of water	L_{vapour}	$2.26 \times 10^{6}\,\mathrm{J\,kg^{-1}}$
atomic mass unit	u	$1.66 \times 10^{-27}\,\mathrm{kg}$
electron volt	eV	$1.60 \times 10^{-19}\,\mathrm{J}$
mass of electron	m_e	$9.109\,383\,5 \times 10^{-31}\,\mathrm{kg}$
mass of proton	m_p	$1.672\,621\,9 \times 10^{-27}\,\mathrm{kg}$
mass of neutron	m_n	$1.674\,927\,5 \times 10^{-27}\,\mathrm{kg}$
speed of light in a vacuum	c	$3 \times 10^{8}\,\mathrm{m\,s^{-1}}$
charge of electron	e	$-1.60 \times 10^{-19}\,\mathrm{C}$
Unit 2: Linear motion and waves		
approximate acceleration due to gravity on Earth	g	$9.80\,\mathrm{m\,s^{-2}}$
speed of sound in air (at 25°C)	v_s	$346\,\mathrm{m\,s^{-1}}$
Unit 3: Gravity and electromagnetism		
gravitational constant	G	$6.67 \times 10^{-11}\,\mathrm{N\,m^{2}\,kg^{-2}}$
mass of Earth	m_E	$5.97 \times 10^{24}\,\mathrm{kg}$
radius of Earth	r_E	$6.37 \times 10^{6}\,\mathrm{m}$
Coulomb's law constant	k	$9 \times 10^{9}\,\mathrm{N\,m^{2}\,C^{-2}}$
permeability of free space (magnetic constant)	μ_0	$4\pi \times 10^{-7}\,\mathrm{T\,A^{-1}\,m}$
permittivity of free space	ε_0	$8.85 \times 10^{-12}\,\mathrm{C^{2}\,N^{-1}\,m^{-2}}$
Unit 4: Revolutions in modern physics		
Wein's displacement constant	b	$2.898 \times 10^{-3}\,\mathrm{m\,K}$
Planck constant	h	$6.626 \times 10^{-34}\,\mathrm{J\,s}$
Rydberg constant	R	$1.097 \times 10^{7}\,\mathrm{m^{-1}}$
Boltzmann constant	k	$1.38 \times 10^{-23}\,\mathrm{J\,K^{-1}}$

Processing of data
percentage uncertainty (%) $= \frac{\text{absolute uncertainty}}{\text{measurement}} \times 100$
percentage error (%) $= \left\lvert \frac{\text{measured value} - \text{true value}}{\text{true value}} \right\rvert \times 100$

Unit 1: Thermal, nuclear and electrical physics

Topic 1: Heating processes

Concept	
first law of thermodynamics	$\Delta U = Q + W$
specific heat capacity	$Q = mc\Delta T$
latent heat	$Q = mL$
energy efficiency	$\eta = \frac{\text{energy output}}{\text{energy input}} \times \frac{100}{1}\%$
Celsius to Kelvin temperature scale conversion	$T_K = T_C + 273$

Topic 2: Ionising radiation and nuclear reactions

Concept	
half-life	$N = N_0 \left(\frac{1}{2}\right)^n$
logarithms	$\log\left(\frac{1}{2}\right)^n = n\log\left(\frac{1}{2}\right)$
	$\log(xy) = \log(x) + \log(y)$
mass and energy equivalence	$\Delta E = \Delta mc^2$

Topic 3: Electrical circuits

Concept	
current	$I = \frac{q}{t}$
potential difference	$V = \frac{W}{q}$
power	$P = \frac{W}{t}$
resistance in a circuit	$V = IR$
power in a circuit	$P = VI$ $P = I^2R$
resistance in series	$R_t = R_1 + R_2 + \ldots R_n$
resistance in parallel	$\frac{1}{R_t} = \frac{1}{R_1} + \frac{1}{R_2} + \ldots \frac{1}{R_n}$
voltage in a series circuit	$V_t = V_1 + V_2 + \ldots V_n$
current in a parallel circuit	$I_t = I_1 + I_2 + I_3 + \ldots I_n$

Unit 2: Linear motion and waves

Topic 1: Linear motion and force

Concept	
equations of motion with constant acceleration	$v = u + at$
	$s = ut + \frac{1}{2}at^2$
	$v^2 = u^2 + 2as$
momentum	$p = mv$
conservation of momentum	$\Sigma mv_{\text{before}} = \Sigma mv_{\text{after}}$
impulse	$\Delta p = F\Delta t$
second law of motion	$a = \frac{F_{\text{net}}}{m}$
work done	$W = \Delta E$ $W = Fs$
gravitational potential energy	$\Delta E_p = mg\Delta h$
kinetic energy	$E_k = \frac{1}{2}mv^2$
conservation of kinetic energy in elastic collisions	$\sum \frac{1}{2}mv^2_{\text{before}} = \sum \frac{1}{2}mv^2_{\text{after}}$
conservation of momentum	$\Sigma mv_{\text{before}} = \Sigma mv_{\text{after}}$

Topic 2: Waves

Concept	
wave equation	$v = f\lambda$
frequency	$f = \frac{1}{T}$
Standing waves for a pipe open at both ends or a string fixed at both ends	$L = n\frac{\lambda}{2}$
for a pipe closed at one end or a string fixed at one end	$L = (2n-1)\frac{\lambda}{4}$
Snell's law	$\frac{\sin i}{\sin r} = \frac{v_1}{v_2} = \frac{\lambda_1}{\lambda_2} = \frac{n_2}{n_1}$
light intensity	$I \propto \frac{1}{r^2}$

Unit 3: Gravity and electromagnetism

Topic 1: Gravity and motion

Concept	
Projectile motion horizontal component of velocity	$v_x = u_x$
horizontal displacement (with no air resistance)	$s_x = u_x t$
final vertical component of velocity	$v_y = u_y + gt$
	$v_y^2 = u_y^2 + 2gs_y$
vertical displacement	$s_y = u_y t + \frac{1}{2}gt^2$
force due to gravity (weight)	$F_g = mg$
average speed in circular motion	$v = \frac{2\pi r}{T}$
acceleration in circular motion (centripetal acceleration)	$a_c = \frac{v^2}{r}$
force in circular motion (centripetal force)	$F_c = \frac{mv^2}{r}$
law of universal gravitation	$F = \frac{GMm}{r^2}$
gravitational field strength	$g = \frac{F}{m} = \frac{GM}{r^2}$
third law of planetary motion	$\frac{T_a^2}{r_a^3} = \frac{T_b^2}{r_b^3} = \frac{4\pi^2}{GM}$

Topic 2: Electromagnetism

Concept	
Coulomb's law	$F = \frac{1}{4\pi\varepsilon_0}\frac{Qq}{r^2} = \frac{kQq}{r^2}$
electric field strength	$E = \frac{F}{Q} = \frac{1}{4\pi\varepsilon_0}\frac{q}{r^2} = \frac{kq}{r^2}$
work done moving a charge in an electric field	$V = \frac{\Delta U}{q}$
magnetic field on a current-carrying wire	$B = \frac{\mu_0 I}{2\pi r}$
magnetic field inside a solenoid	$B = \mu_0 nI$
magnetic force on a moving charged particle	$F = qvB\sin\theta$
magnetic force on a current-carrying wire	$F = BIL\sin\theta$
magnetic flux	$\phi = BA\cos\theta$
electromagnetic induction: induced emf in coils	$emf = -\frac{N\Delta(BA_\perp)}{\Delta t}$
	$emf = -N\frac{\Delta\phi}{\Delta t}$
power in transformers	$I_p V_p = I_s V_s$
voltage in transformers	$\frac{V_p}{V_s} = \frac{N_p}{N_s}$

Unit 4: Revolutions in modern physics

Topic 1: Special relativity

Concept	
time dilation	$t = \frac{t_0}{\sqrt{\left(1 - \frac{v^2}{c^2}\right)}}$
length contraction	$L = L_0\sqrt{\left(1 - \frac{v^2}{c^2}\right)}$
relativistic momentum	$p_v = \frac{m_0 v}{\sqrt{\left(1 - \frac{v^2}{c^2}\right)}}$
mass–energy equivalence	$\Delta E = \Delta mc^2$

Topic 2: Quantum theory

Concept	
Wien's law	$\lambda_{max} = \frac{b}{T}$
photon energy	$E = hf = \frac{hc}{\lambda}$
photoelectric effect	$E_k = hf - W$
	$W = hf_0$
de Broglie wavelength	$\lambda = \frac{h}{p}$
Bohr's model of the atom and atomic energy states	$mvr = \frac{nh}{2\pi}$
	$n\lambda = 2\pi r$
Rydberg formula	$\frac{1}{\lambda} = R\left(\frac{1}{n_f^2} - \frac{1}{n_i^2}\right)$

Topic 3: The Standard Model

Concept	
conservation of baryon number	$B = n_b + n_{\bar{b}}$
	$B = \frac{1}{3}\left(n_q - n_{\bar{q}}\right)$
conservation of lepton number	$L = n_l + n_{\bar{l}}$

Group

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18

Period 1

1	2
1 H 1.01	

2

3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
3 Li 6.94	4 Be 9.01									5 B 10.81	6 C 12.01	7 N 14.01	8 O 16.00	9 F 19.00	2 He 4.00
11 Na 22.99	12 Mg 24.31									13 Al 26.98	14 Si 28.09	15 P 30.97	16 S 32.06	17 Cl 35.45	10 Ne 20.18
19 K 39.10	20 Ca 40.08	21 Sc 44.96	22 Ti 47.90	23 V 50.94	24 Cr 52.00	25 Mn 54.94	26 Fe 55.85	27 Co 58.93	28 Ni 58.71	29 Cu 63.54	30 Zn 65.37	31 Ga 69.72	32 Ge 72.59	33 As 74.92	34 Se 78.96	35 Br 79.91	18 Ar 39.95
37 Rb 85.47	38 Sr 87.62	39 Y 88.91	40 Zr 91.22	41 Nb 92.91	42 Mo 95.94	43 Tc (99)	44 Ru 101.07	45 Rh 102.91	46 Pd 106.4	47 Ag 107.87	48 Cd 112.40	49 In 114.82	50 Sn 118.69	51 Sb 121.75	52 Te 127.60	53 I 126.90	36 Kr 83.80
55 Cs 132.91	56 Ba 137.34	57 La 138.91	72 Hf 178.49	73 Ta 180.95	74 W 183.85	75 Re 186.2	76 Os 190.2	77 Ir 192.2	78 Pt 195.09	79 Au 196.97	80 Hg 200.59	81 Tl 204.37	82 Pb 207.19	83 Bi 208.98	84 Po (210)	85 At (210)	54 Xe 131.30
87 Fr (223)	88 Ra (226)	89 Ac (227)	104 Rf (261)	105 Db (262)	106 Sg (263)	107 Bh (264)	108 Hs (277)	109 Mt (268)	110 Ds (271)	111 Rg (272)	112 Cn (277)	113 Nh (284)	114 Fl (289)	115 Mc (288)	116 Lv (293)	117 Ts (294)	86 Rn (222)
																	118 Og (294)

Lanthanides

58 Ce 140.12	59 Pr 140.91	60 Nd 144.24	61 Pm (145)	62 Sm 150.35	63 Eu 151.96	64 Gd 157.25	65 Tb 158.92	66 Dy 162.50	67 Ho 164.93	68 Er 167.26	69 Tm 168.93	70 Yb 173.04	71 Lu 174.97

Actinides

90 Th 232.04	91 Pa (231)	92 U 238.03	93 Np (237)	94 Pu (242)	95 Am (243)	96 Cm (247)	97 Bk (247)	98 Cf (249)	99 Es (254)	100 Fm (253)	101 Md (256)	102 No (254)	103 Lr (257)

1 ← Atomic number
H ← Symbol
1.01 ← Relative atomic mass*

Every isotope of these elements is radioactive.

*Brackets indicate the relative atomic mass of the isotope with the longest half-life.

Glossary

A

absolute measurement uncertainty The range within which the true value of a measurement is thought to be, estimated using the level of precision of the measurement device. Also known as limiting error.

absorption spectrum Spectrum containing dark lines in the positions of the wavelengths that are absorbed by a gas as light passes through it. This is related to the emission spectrum of the gas.

absolute uncertainty of the mean. The range within which the mean of the dependent variable falls. This is found from the maximum value and minimum value of the dependent variable across the set of trials using the formula:

$$\Delta\bar{x} = \pm\frac{x_{max} - x_{min}}{2}.$$

acceleration The rate of change in velocity of an object over time, Acceleration can involve an increase or decrease in speed and is a vector quantity. (Symbol, α; SI unit, m/s^2).

acceleration due to gravity The rate at which a falling object will accelerate in a gravitational field. Equivalent to the gravitational field strength. (Symbol, *g*; unit, m/s^2)

accuracy The closeness of a measured or observed value is to the true or accepted value.

aether An invisible, massless, rigid substance that was proposed as the medium in which light waves propagate. There is no experimental evidence for the existence of the aether.

alternating current (AC) An electric current typically used in power supplies that reverses direction many times per second.

altitude Height above ground level.

angle The difference between the directions of two lines.

annihilation The process in which matter is completely converted into energy. This is not a chemical process in which matter in one form is converted to matter in another form, as in burning.

antiparticle A subatomic particle that has the same properties of mass, charge and lifespan as their corresponding matter particle, but have electric charge and quantum numbers of opposite sign. For example a positron is the antiparticle of an electron.

aphelion The point in a planet's orbit where it is closest to the Sun.

applied force A force acting on an object that is usually in the same direction as the motion. It is usually from an engine or motor.

armature A revolving structure in an electric motor or generator, wound with the coils that carry the current. It rotates within a magnetic field to induce an EMF.

atomic clock A clock with an accuracy of 1 second in 1.4 million years, and the ability to measure time to an incredible number of decimal places.

average speed The measurement the distance travelled over the time taken by an object. Average speed is a scalar quantity. (Symbol, v; SI unit, m/s or ms^{-1}).

average velocity The rate of change of displacement calculated by the formula

$$\text{average velocity} = \frac{\text{displacement}}{\text{time}}.$$

B

baryon number A quantum number that represents the total number of baryons involved in an interaction. The baryon number, B, is dependent on whether the particles are baryons (+1), anti-baryons (−1) or neither (0). The number is conserved, meaning that the number before and after the reaction is the same. It is defined by $B = \frac{1}{3}(n_q - n_{\bar{q}})$, where n_q is the number of quarks and $n_{\bar{q}}$ is the number of antiquarks.

baryon A subatomic particle composed of three quarks and experiences the strong nuclear force. Protons and neutrons are examples of baryons.

bias In scientific research, bias is the deviation from truth, systematic errors, that can lead to inaccurate results and conclusions. It can stem from personal prejudice and can occur at any stage of research, including data collection, analysis, interpretation or publication.

black body A body that does not reflect any radiation. It does not necessarily have to be black; for instance, the Sun can be modelled as a black body.

C

centripetal acceleration The acceleration directed towards the centre of the circle when an object moves with constant speed in a circular path.

centripetal force The force that causes an object to travel in a circular path, e.g. gravity, tension, normal force and friction.

claim A statement made that a phenomenon is true, without evidence to support it.

classical physics A name for non-quantum physics or events happening at non-relativistic speeds.

coefficient of determination (R^2) A calculated value that indicates the ability to predict the dependent variable value from the independent variable value.

coherent Waves that are in phase i.e. at the same stage at the same time.

colour charge A property of quarks. Quarks can have a red, green or blue colour charge; antiquarks can have an antired, antiblue or antigreen colour charge. The colour charge of hadrons (particles made of quarks) must always be white; for example as red + blue + green or red + antired.

Coulomb's law The law of electrostatic force between two point charges that is proportional to the product of the two charges and the inverse square of the distance between them. This is expressed by the formula:

$$F = \frac{1}{4\pi\varepsilon_0}\frac{Qq}{r^2} = \frac{kQq}{r^2}.$$

commutator Part of an electric motor that allows current to be reversed, enabling the coil to keep rotating due to magnetic force.

component The proportion of a vector that can be considered to be acting in a particular direction.

Compton scattering The inelastic scattering of a photon by an electron, demonstrating light has momentum.

constructive interference A process by which two or more waves combine to reinforce each other. The amplitude of the resulting wave is equal to the sum of the amplitudes of the superimposed waves.

continuous spectrum Spectrum of light in which every wavelength is produced. Also known as broadband radiation.

controlled variable A variable that is controlled during an experiment so that it does not change and does not influence the measured results or dependent variable.

D

data The measurements or observations collected during an investigation.

destructive interference A result observed when waves interact and the amplitude of the resulting wave is equal to the difference between the amplitudes of the superimposed waves.

diffraction The bending of waves around an obstacle or through gaps in a barrier.

dipolar Having two poles, both a north and south, like a bar magnet.

dipole A magnetic dipole has both a north and south pole. Magnetic poles only exist as dipoles.

displacement The change in position of an object relative to the origin. Displacement is a vector quantity. (Symbol, *s*; SI unit, m).

double-slit experiment Thomas Young's experiment demonstrated the wave nature of light by showing that when light passes through two narrow slits, it creates an interference pattern of bright and dark fringes on a screen.

drag Air resistance, or the retarding force that an object experiences when moving through a gas or a liquid.

E

eccentricity The level of deviation between an elliptical orbit and a circular orbit. An eccentricity of 0 would be a circle. As the orbit becomes more elliptical, the value increases toward 1.

electric field strength A measure of the force per unit charge on a charged object within an electric field, with units $N\,C^{-1}$. Electric field strength can also be a measure of the difference in electrical potential per unit distance, with units $V\,m^{-1}$.

electric fields A region of space where charged objects experience a force due to the field created by another charged object.

electrical potential The work required (per unit charge) to move a positive point charge from infinity to a place in the electric field (units $J\,C^{-1}$).

electrical potential energy A form of energy that is stored in the field, *U*.

electromagnet A magnet consisting of an iron core wound with a coil of wire, through which a current is passed. The core only becomes magnetised when current is flowing.

electromagnetic induction The creation of an electric current, or an EMF, in a loop of wire as the result of a changing magnetic flux through the loop.

electromagnetic radiation Energy emitted in continuous waves with two transverse, mutually perpendicular components. It is comprised of a varying magnetic field and a varying electric field.

electromagnetic (EM) spectrum The range of all possible frequencies of EM radiation. The visible spectrum is just one small part of the EM spectrum.

electromotive force A voltage, or potential difference rather than a force, created by a device such as a battery, generator or other source of electrical potential. The abbreviation is written as EMF. (Symbol, emf; SI unit,V).

electron gun A device for producing a narrow stream of electrons from a heated cathode.

electron volt A small unit of energy. One electron volt (1eV) is the energy an electron would gain when accelerated across a potential difference of one volt: $1\ \text{eV} = 1.6 \times 10^{-19}$ J.

electrostatic force Electrostatic force is the force that acts between two charged objects due to their electric charges. Like charges (both positive or both negative) repel each other, while opposite charges (positive and negative) attract each other. This force is a fundamental part of electromagnetism and is governed by Coulomb's Law.

elementary particle A fundamental subatomic particle that has no known substructure or comprised of smaller particles.

ellipse Can be likened to a flattened circle.

emission spectrum A set of specific wavelengths emitted by an atom or molecule that is unique to the atom or molecule.

energy level diagram A diagram that represents the energy levels occupied by electrons in any particular atom.

energy levels The orbital levels in which electrons orbiting the nucleus of an atom can remain stable.

error A measure of the estimated difference between the observed or calculated value of a quantity and its true value.

error bars Graphical representations on graphs to show the variability of data and thus indicate the uncertainty in a measurement.

ethics Moral principles governing people's behaviour.

extend In science, to make an alteration to an experiment that will enable further investigation and understanding to be developed through the results.

extrapolate Extend or project information or data beyond what is measured or known to predict or infer an unknown situation.

F

fact Something that is known to be true.

Faraday's law of induction The average EMF generated in a coil is proportional to the rate of change of magnetic flux and the number of turns in the coil.

Fermion An elementary particle that makes up atoms, e.g. quarks and electrons, or composite particles, such as protons and neutrons. Bosons are elementary particles that are not fermions.

ferromagnetic materials Materials that experience more magnetism than other materials; they are permanent magnets that can be easily magnetised.

field A region of space around an object where a force can be felt by other objects.

field lines A pictorial representation of the strength and direction of a field. The lines designate the direction of the field, while their density represents its relative strength.

focus Each ellipse has two focus points. The sun is at one focus of every planet's orbit; there is nothing at the other focus.

force A push or pull between interacting objects, which can result in one or both objects to change their velocity, direction or shape. Forces can occur by physical contact interactions, such as frictional and tension forces, or by non-contact interactions such as gravitational, electrical and magnetic forces. (Symbol, F; SI unit, N).

force due to gravity (also referred to as weight or gravitational force) The force on an object due to its mass being in the presence of a gravitational field.

frame of reference A coordinate system that is based on the position of an object or observer.

free-body diagram A diagram that shows only the forces directly acting on a single object.

freefall An object is said to be in freefall if the only force acting on it is its weight, i.e. the force of gravity. Any object in outer space is in freefall, as is a rock dropped from a height on Earth before air resistance acts on it.

frequency The number of waves passing a given point in one second or the number of repeats of a cycle each second. Measured in hertz (Hz).

frictional force A force that acts on an object to oppose its motion.

fundamental Serves as the foundation from which everything else evolves or develops.

G

gauge boson Elementary particles that transmit forces, mediating interactions between particles. These forces include electromagnetic, strong and weak forces. There are four gauge bosons in the Standard Model: the gluon, photon, Z boson and W boson. There are four gauge bosons in the Standard Model: the gluon, photon, Z boson and W boson.

gluon An elementary particle that acts as an exchange particle for the strong nuclear force between quarks, similar to the exchange of photons in the electromagnetic force between two charged particles. Gluons carry the colour charge of the strong interaction. They can be considered to be the fundamental exchange particle underlying the strong interaction between protons and neutrons in a nucleus.

graph A diagram showing the relationship between variables.

gravitational constant The universal constant, $G = 6.67 \times 10^{-11}\ \text{N m}^2\text{kg}^{-2}$.

gravitational field strength The strength of gravity, usually measured at the surface of a planet or moon. It is equivalent to the acceleration due to gravity, g, and measured in newtons per kilogram (N kg^{-1}).

gravitational field The region around an object where other objects will experience a gravitational force.

gravitational force The force applied on a mass by a gravitational field.

H

hadron A composite particle that contains quarks held together by the strong force. Hadrons are subdivided into two families: baryons (e.g. the proton and neutron) and mesons (e.g. the pion and kaon).

hypothesis A proposed explanation for an observed phenomenon. It is a prediction based on scientific reasoning that can be tested experimentally.

I

ideal transformer A transformer that is 100% efficient and in which the input power and the output power are equal. Real transformers are close to being ideal.

inclined plane A flat surface at an angle to the horizontal that acts as an aid to lifting or lowering a massive object.

induced current Electric current produced by changing a magnetic flux in the region of a conductor or by moving the conductor in a magnetic field.

inertial frame of reference A frame of reference that is either moving with constant velocity or is stationary (i.e. it is not accelerating).

infrared (IR) A non-visible section of the electromagnetic spectrum with wavelengths longer than those of visible light.

interference The process in which two or more waves combine to reinforce or weaken each other. The amplitude of the resulting wave is equal to the vector sum of the amplitudes of the superimposed waves.

International system (SI) A globally recognised measurement system based on the metric system.

inverse square law A physical law in which some quantity (e.g. gravitational force) is inversely proportional to distance squared.

ionisation The process of adding or removing electrons of an atom, resulting in a negative or positive charge.

L

laws Scientific laws are statements that describes or predicts natural phenomena. Laws do not explain why an event occurs, only that it happens the same way consistently.

Law of Universal Gravitation The attractive force between two masses due to gravity is directly proportional to the product of their masses and inversely proportional to the square of the distance between them.

length contraction When an object's length is measured in a moving frame of reference is less when measured by a stationary observer.

Lenz's law The direction of the induced current in a conductor is such that its associated magnetic field opposes the change in flux that caused the current.

lepton number A quantum number which is conserved in particle interactions. There are three varieties of lepton number: electron, muon, and tau. Each is conserved using $L = n_1 - n_1^-$, where nl is the number of leptons and n_1^- is the number of antileptons.

lepton An elemetary particle that has a charge and that interacts via the weak nuclear force. there are six flavours of leptons in the Standard Model: electron, electron neutrino, muon, muon neutrino, tau and tau neutrino.

line of best fit A straight line that best represents scatter-plot data but does not necessarily pass through all points.

Lorentz Force A force acting on a charged particle in a magnetic field.

M

magnetic Describes a material having properties of magnetism.

magnetic field A region influenced by a magnet.

magnetic field lines Visual representation of the magnetic field, used to show the direction of a magnetic field in diagrams.

magnetic flux The strength of a field in a given area expressed as the product of the area and the component of the field strength at right angles to the area.

magnetic flux density The amount of magnetic flux per unit area, i.e. the closeness of magnetic field lines. Same as magnetic field strength.

magnetic force The force exerted by a magnet on a moving, charged particle.

magnetic pole A region at the end of a magnet at which the field of the magnet is most intense. Field lines flow from the north pole to the south pole.

magnetism A physical phenomenon caused by magnets, that results in a field that attracts or repels other magnetic materials.

major axis The major axis of an ellipse is a line that passes through both foci. It is the greatest distance between two points on an elliptical orbit.

mean A calculated value that represents the centre of a set of numbers that have been averaged.

measured variable A variable that is measured during an experiment because it cannot be controlled, and must be known so that any influence on the measured results or dependent variable can be determined.

median The value in the middle of an ordered list of values.

medium A physical substance, such as air or water, through which a mechanical wave is propagated.

meson A subatomic particle comprised of a quark and an antiquark, referred to as a quark–antiquark pair. Mesons interact via strong nuclear forces and are unstable, short-lived particles. Examples of these are pion and kaon.

methodology A systematic process used to conduct a study guiding the process of data collection, analysis and interpretations to produce reliable and valid results.

mode The value that occurs most frequently in a list of values.

model A representation, standard or example.

modify To change the form or qualities of something.

muon A high-velocity unstable subatomic particle. It is a lepton similar to the electron but with a heavier mass.

N

neutrino An almost massless, neutral particle released during some nuclear reactions.

non-inertial frame of reference A frame of reference in which a body does not seem to be acting in accordance with inertia, i.e. it is undergoing acceleration.

normal force The force exerted by a surface that acts perpendicular (at right angles) to the surface, pushing back against an object in contact with it. It is often referred to as the apparent weight of the object. (Symbol, F_N; SI unit, N).

O

observation Witnessing an event or phenomenon.

outlier A data point that lies outside the main group of data.

P

pair production The creation of a particle and its antiparticle. This is commonly the result of two photons interacting or a photon interacting with an atomic nucleus.

Parallel Lines, planes or surfaces that are always the same distance apart and never cross.

particle interaction diagram Also known as Feynman diagrams, a pictorial representation of the interactions of quantum particles in space (y-axis) and time (x-axis).

peer-reviewed Work critically reviewed by other specialist scientists.

percentage uncertainty The uncertainty of a measurement expressed as a percentage of the measurement.

perihelion The point in a planet's orbit where it is furthest from the Sun.

period The time interval taken to complete one cycle of a regularly repeating phenomenon, such as a rotating object or in a sound wave. The SI unit is seconds (s).

permanent magnet Material that holds magnetic properties over a long period of time, or indefinitely; e.g. the magnets on your refrigerator.

permeability of a vacuum A constant, $\mu_0 = 4\pi \times 10^{-7}\,\mathrm{T\,m\,A^{-1}}$, representing the proportionality that exists between magnetic flux density and magnetic field strength in the medium.

perpendicular At right angles (90°) to.

personal protective equipment (PPE) The equipment specifically designed and used during activities to protect the user from hazards.

phenomenon (pl. phenomena) An event that can be observed, measured and described.

photocurrent Current caused by the flow of photoelectrons during the photoelectric effect.

photoelectric effect The spontaneous emission of electrons from the surface of some metals if light of the appropriate wavelength is shone on their surface.

photoelectron An electron released from an atom due to the photoelectric effect.

photon A packet or bundle of electromagnetic radiation such as light.

plagiarism Taking someone else's idea or work and passing it off as your own.

point charge A ideal situation in which all of the charge on an object is considered to be concentrated at a single point. The point size is negligible in relation to the distance between it and another point charge.

pole The end of a magnet is referred to as a magnetic pole.

postulates of special relativity The first postulate states that the laws of physics are the same in any inertial (non-accelerated) frames of reference and the second states that the speed of light has a constant value for all observers regardless of their motion or the motion of the source.

potential difference The difference in the electric potential between two points in an electric field. This can be used to calculate the work that will be done on a charged particle moving through this field (unit, V).

precision The ability to consistently obtain the same measurement. To obtain precise results, you must minimise random errors.

prefix Specific letters added before a root word to modify its meaning. For example, adding 'centi' to 'metre' to form centimetre (cm), changes the meaning of being 1 hundredth $\left(\frac{1}{100}\text{ th}\right)$ of a metre.

primary source The original source from which information was created or data was measured.

principle In the context of science, a fundamental concept or rule to explain how something works.

processed data Data that has been manipulated to produce meaningful information; a set of displayed data in an appropriate form such as tables or graphs; required information that has been extracted from a set.

projectile An object that is fired, kicked, thrown or otherwise moving under the influence of a gravitational field.

proper length The length of an object as measured in the frame of reference in which the object is stationary.

proper time interval The time between two events that occur at the same point in space.

Pythagoras' theorem States that in a right-angled triangle the square of the hypotenuse is equal to the sum of the squares of the two other sides. Given by $c^2 = a^2 + b^2$.

Q

qualitative data Non-numeric data from categorical variables that can be counted but not measured, e.g. colour and brightness.

quantitative data Numeric data from variables that can be measured, e.g. wavelength and temperature.

quantum The name given to a defined (small) amount of energy. Each quantum has an energy proportional to its frequency according to the equation $E = hf$.

quantum number A set of numbers that describe the specific locations and states of a particle.

quark A fundamental subatomic particle that combines to form hundreds of different particles known as hadrons. Currently there are six different quarks: up, down, charm, strange, top and bottom.

R

random error Unpredictable variations in the measurement process. They are present in all measurements except those involving counting. Random errors affect the precision of a measurement. They can be reduced by making more or repeated measurements and calculating a new mean and/or by refining the measurement method or technique.

range The variation in values between upper and lower limits on a particular scale or the largest and smallest measurements.

raw data Data that has not been processed or analysed.

redirect To adjust the methodology to explore new aspects or gain deeper insight into the phenomena observed in the initial experiment.

reference list A list of resources that are cited or referred to in the document.

refine In the context of a science experiment, to modify the methodology for greater accuracy, precision or clarity often leading to improved outcomes.

regression The calculated estimate of the strength of a relationship between variables.

relativistic length The measured length of an object in a frame of reference where it is moving. (Symbol, L; SI unit, m).

relativistic momentum The measured momentum of an object in the frame of reference where the object is moving. (Symbol, p_v; SI unit, N s).

relativistic time interval The time interval measured in a frame of reference where the object is observed moving. (Symbol, t; SI unit, s).

replication (or repeat trials) The process of repeatedly conducting or choosing a process, activity, trial or sample in an attempt to replicate the results, event or set up.

resolution The measure of an instrument's ability to separate two points. It is called the resolving power of an instrument.

resolve To find the component of a vector in each of two directions (e.g. horizontal and vertical or north and east).

rest mass The mass of an object measured in a reference frame where it is at rest relative to the observer.

right-hand grip rule Method for determining the direction of the magnetic field around a current-carrying wire by curling the fingers of the right hand around the wire with the thumb pointing in the direction of the current (and vice versa).

right-hand slap rule Method for determining the direction of the magnetic force acting on a current-carrying wire by pointing the thumb of the right hand in the direction of the current and the fingers in the direction of the magnetic field. The direction of the force is outwards from the palm.

risk assessment An activity to identify, assess and control hazards.

S

safety data sheet (SDS) A document that outlines specific details about items that are required to be considered when handling the item for experimentation.

sample size The number of individual measurements or observations undertaken for each tested variable.

satellite An object in a stable orbit around a central body. Could be natural, like a planet, or artificial, like a communications satellite.

scientific journal A book containing the entire collection of work related to an experiment or investigation.

scientific method A systematic process designed to minimise biases and improve the replicability of experiments to gain knowledge and understanding of the world. The steps typically include observation, question formulation, experimentation, data analysis and drawing conclusions.

scientific notation A measured value written as a mathematical expression, between 1 and 10 including decimals, displaying all significant figures, multiplied by 10 raised to a specific power.

secondary source A source of information or data that was not created or measured by its author, but which cites another source.

semi-major axis Half the length of the major axis of an ellipse.

significant figures The digits recorded according to the precision of an instrument; the digits in a calculation that represent the precision of an instrument.

simultaneity The relationship between two events that occur at the same time in a given frame of reference.

simultaneous Events occurring at the same time.

single-photon double-slit experiment The double-slit experiment where light is passed through two slits to produce an interference pattern but conducted with one photon at a time, thus showing each individual photon is producing interference. This experiment provides evidence of both wave and the particle nature of light.

solenoid Coil of many turns of wire that can be used as an electromagnet.

Standard Model A mathematical description of all known particles and three of the forces acting on them. It is currently the most successful theory for predicting the behaviour and properties of the particles that exist in nature.

standing wave The periodic disturbance in a medium resulting from the combination of two waves of equal frequency and intensity travelling in opposite directions. Also called a stationary wave.

step-down transformer Device that decreases the secondary voltage compared to the primary voltage.

step-up transformer Device that increases the secondary voltage compared to the primary voltage.

stopping voltage The applied voltage required to stop all photoelectrons from reaching the collector electrode. For a particular frequency of incident light on a particular metal, the stopping voltage is a constant.

strong nuclear force A short-range but powerful force of (mostly) attraction that acts between all the nucleons in the nucleus. The strong nuclear force acts on quarks and binds them together in hadrons. It also acts to bind protons and neutrons together within atomic nuclei.

systematic errors Errors that cause readings to differ from the true value by a consistent amount each time a measurement is made, i.e. all readings are shifted in one direction from the true value. Systematic errors affect the accuracy of a measurement and the accuracy cannot be improved by repeating those measurements.

T

temporary magnet Material, such as soft iron, that will temporarily gain magnetic properties when exposed to a strong magnetic field.

tension A force that acts along a string or wire that supports a massive object. The direction of this force is away from the object but along the string or wire.

theories Evidenced-based explanations of occurring phenomena.

threshold frequency The minimum frequency of electromagnetic radiation for which the photoelectric effect can occur for a given material.

time dilation When an observer watches events in a frame of reference that is moving very fast relative to them, time in that frame of reference will appear to go more slowly. People in the moving frame do not experience any difference in the rate at which time passes. This effect is one of the results of Einstein's theory of special relativity.

transformer A device that transfers an alternating current from one circuit to one or more other circuits, usually with an increase (step-up transformer), or decrease (step-down transformer) in voltage. The input goes to a primary coil; the output is taken from a secondary coil or windings linked by induction to a primary coil.

U

ultraviolet (UV) A non-visible section of the electromagnetic spectrum with wavelengths shorter than those of visible light.

uncertainty A range of measurements from the experiment within which the true value is thought to be.

uniform circular motion The motion of an object travelling in a circular path at a constant speed while constantly changing direction, resulting in the velocity constantly changing.

V

valid Something is well-founded and supported by evidence or reasoning.

validity A measurement is said to be valid if it measures what it is supposed to be measuring. An experiment is said to be valid if it investigates what it sets out and/or claims to investigate.

variable A factor or condition that can change.

vector A variable that requires both a magnitude and a direction. Examples include acceleration and displacement.

velocity The measure of an object's speed in a specific direction. Velocity is a vector quantity as it has both magnitude and direction.

velocity The rate of change of displacement of an object. (Symbol, v; SI unit, m/s); if the rate of change is measured at an instant in time then this is an instantaneous velocity; if the rate of change is calculated using the formula $\text{velocity} = \frac{\text{displacement}}{\text{time}}$, then this is average velocity.

visible light Light that can be seen by human eyes. It is part of the electromagnetic spectrum, with wavelengths between about 400 and 800 nm.

W

W^+, W^- and Z^0 The gauge bosons that mediate the weak nuclear force.

wave A phenomenon by which energy is moved from place to place due to vibrations. Sound and water waves require material to carry them, but light waves do not.

wave–particle duality Light exhibits both wave and particle behaviour.

weak nuclear force One of four of the fundamental forces that plays a role in nuclear reactions, responsible for radioactive decay, and particle reactions. It is mediated by W and Z bosons.

weight Force due to gravity that acts on any mass in a gravitational field. (Symbol, F_g or W; SI unit, N).

work function The energy required to remove an electron from an atom. It is measured in joules or electron volts.

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Attributions

The following abbreviations are used in this list: t = top, b = bottom, l = left, r = right, c = centre.

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